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A study of hybrid propulsion system on forklift trucks

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Abstract

This paper discusses the hybrid systems used to power forklift trucks and presents an effective hybrid propulsion system. There are many advantages to applying the hybrid system to engine forklifts: dynamic operating patterns, speed, and torque. The engine forklift is tested to investigate the request torque and speed pattern at the VDI cycle, and the speed pattern of the forklift is demonstrated by comparing it with the Manhattan Bus cycle and the FTP72 cycle. The hybrid propulsion system is suggested to improve fuel economy preserving the drive ability and grade ability of engine forklift. Lastly, the simulation results of this hybrid configuration are shown, and the improvement factors of fuel economy are briefly demonstrated.

Keywords: hybrid forklift, hybrid propulsion system, hybridization suitability, engine and battery hybrid

1 Introduction

Forklift trucks consist of powertrain systems to provide both driving and handling functions, such as lifting. The power sources of the forklift typically are diesel engines, gasoline engines, LPG engines, and storage batteries with electric motors. Electric forklifts are usually limited to work outside because they have limited by energy capacity and the road traffic restrictions of government. However, engine forklifts are utilized on roads, and they are widely used in the forklift truck industry.

Traditionally, research and development in the forklift truck industry has focused on drivability, lifting performance, durability, reliability, and cost. However, the fuel economy of the engine forklift has recently become an important aspect of its performance and therefore a major marketing point. In addition, high oil prices and emissions regulations of developed countries have accelerated the development of fuel-efficient forklifts. In terms of fuel economy, the hybrid system, which uses a combination of engine and battery, is appropriate for powering forklifts because of the particular working cycles of each.

Previous research showed that several kinds of hybrid forklifts have been developed by Toyota and Mitsubishi Heavy Industries (MHI) (Still et al., 2009). In its hybrid electric vehicle in the PRIUS series, Toyota has developed 3.5 to 4.5 ton hybrid forklifts called Geneo-Hybrid with an engine and Ni-MH-type battery. MHI has also developed 4.0 to 5.0 ton hybrid forklifts consisting of an engine and a battery (lithium-ion) [1]. Komatsu and Still (2011) have also developed a hybrid forklift using their own hybrid concepts.

This paper demonstrates the suitability of hybrid systems to power forklift trucks and presents an effective hybrid propulsion system. The engine forklift was tested to analyze the request power and speed pattern at the VDI cycle, and the speed pattern was compared with that of a bus and a passenger car. The hybrid system on the forklift was then designed based on the results of the analysis, We suggest that this hybrid propulsion system improves fuel economy while preserving drive and grade ability. The simulation results of this hybrid configuration are shown, and the improvement factors of fuel economy are demonstrated briefly.

2 The suitability of the hybrid system for forklifts

2.1 Test environment of an engine forklift

In order to investigate suitability of the hybrid system to power forklifts, an engine forklift was tested. The test model of the engine forklift is the 50DE-7 diesel engine forklift produced by Hyundai Heavy Industries (HHI), as shown as Figure 1. Figure 1 also shows data acquisition equipment (DAQ) and pressure sensors. The transmission control unit (TCU) transmits the gear level, engine speed, turbine speed, and vehicle speed to the DAQ through controller area network (CAN) communication. The pressure sensors measure the pressures of lifting, steering and braking part of the pump.

The power transfer system in the engine forklift is shown in Figure 2, which indicates that the power system of the engine is divided into the hydraulic part and driving part. The request power is generated by the diesel engine and is distributed to the hydraulic pump and transmission in the 50DE-7. The hydraulic power is the request power applied to load, braking, and steering operations. Because a fixed volume pump is applied to this engine forklift, the amount of discharge from the pump depends on the engine speed. For example, the engine is operated at a high speed to lift the fork quickly.

In the driving part, the transmission power is responsible for driving the forklift. A torque converter is connected to the transmission to reduce shock to the gearshift, which is convenient for the operator. However, much power loss occurs in the transfer of fluid power. The output power is transferred from the transmission to the drive axle, and it then drives the wheels. When an operator handles the hydraulic part independently, operator controls the inching pedal that functions to disconnect the power flow between the engine and the transmission.

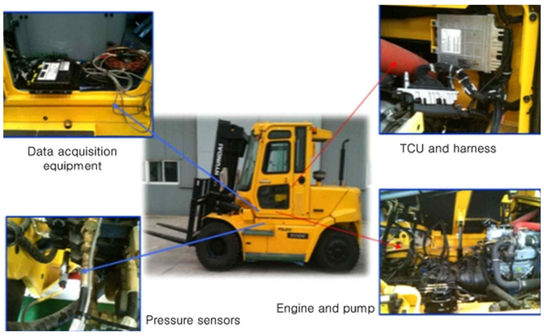

Figure 1: Engine forklift and test equipment

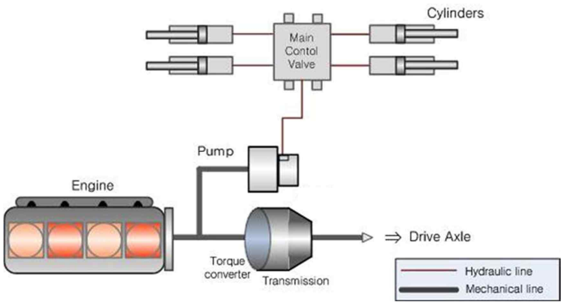

Figure 2: Power transfer system of the engine forklift

2.2 Fuel consumption test course of forklift (VDI cycle)

Figure 3 shows the VDI cycle test environment used to measure fuel consumption as a unit of liter per hour (l/h). The test conditions are shown in Table 1.

The VDI cycle describes the pattern of ordinary usage of the forklift. When it reaches the VDI cycle, the forklift moves from A position to C position by reverse travel and then drives to the B position by toward travel. At the B position, the driver operates the load-handling devices, such as lifting and tilting, according to the test conditions shown in in Table 1. The driver lifts the full load weight by 2 m and then lowers it. The forklift is then returned to A position and the procedure is repeated. It is defines one cycle of VDI, which has carried out for 60 seconds. The VDI cycle is used in test cycles to measure the fuel consumption of forklifts. However, results differ depending on the operating time of the work device and the acceleration and deceleration by the driver. Therefore, we tested the forklift in the VDI cycle repeatedly to calculate the average value of fuel consumption in liters per hour (l/h).

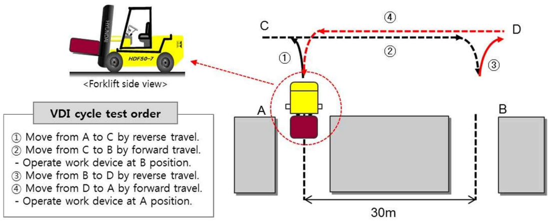

Figure 3: VDI cycle test course

Table 1: VDI cycle test condition

	Test condition
Distance	30 m
load level	full load weight (5 ton)
work operation	Tilt out → Lift up 2 m → Lift down 2 m → Tilt in
cycle time	60 sec
gear level	second gear

2.3 Test results and analysis

Figures 4 and 5 show the test results of the speed and power of the engine forklift in the VDI cycle respectively. The forklift was driven from A to B (Figure 3) for the first 20 seconds. The forklift was driven in reverse from A to C, (shown as number 1 in Figure 4), and then driven forward from C to B (number 2). In this drive test, the maximum speed of the forklift was approximately 15 km/h, and the maximum acceleration rate was 1.6 m/s^2. The load handling operation was conducted at B. Although the most hydraulic power was consumed during the load handling operation, it was also consumed during driving because of the braking and steering operation. Because the maximum drive power was greater than the maximum hydraulic power, the energy used in driving accounted for the greatest part of the energy consumption.

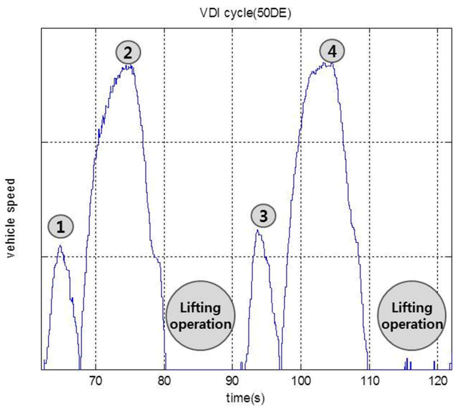

Figure 4: Engine forklift speed (VDI cycle)

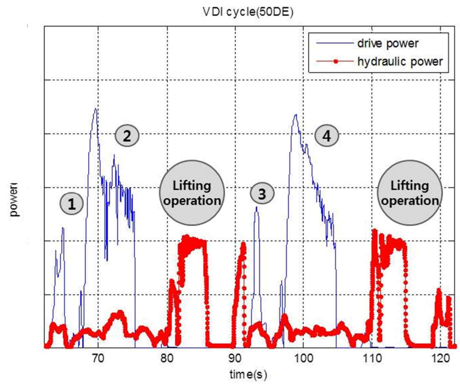

Figure 5: Engine forklift power (VDI cycle)

Figure 6 shows the comparison of speed among the forklift, bus, and passenger car in the range of 0 to 300 seconds. These are described by the VDI cycle, Manhattan Bus cycle and FTP72 cycle, respectively, and the FPT72 shows the speed of the passenger car in the city. In contrast, in other profiles, the VDI cycle repeated certain speed patterns. Furthermore, because the forklift was driven at less than 20 km/h, its speed profile is a combination of acceleration and deceleration.

Figure 7 shows the proportions of acceleration and deceleration. It is well known that the hybrid system is more efficient in the city cycle than in the highway cycle because of the large proportion of acceleration and deceleration [2, 3]. The proportion of acceleration rate (over 0.5 m/s^2 or under –0.5 m/s^2) exceeded 50% in the VDI cycle, which is similar to the Manhattan bus cycle. When the forklift was accelerated at a low speed with high torque, the motor was more efficient than the engine was. In addition, regenerative energy was stored in the battery during deceleration through regenerative braking.

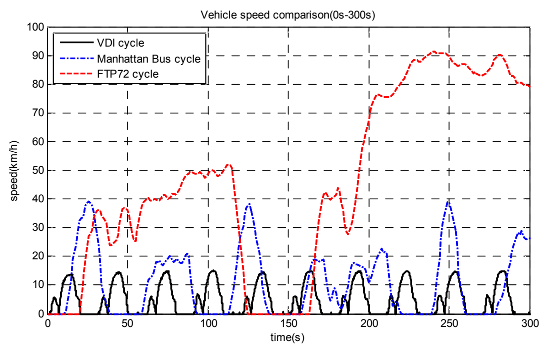

Figure 6: Speed comparison

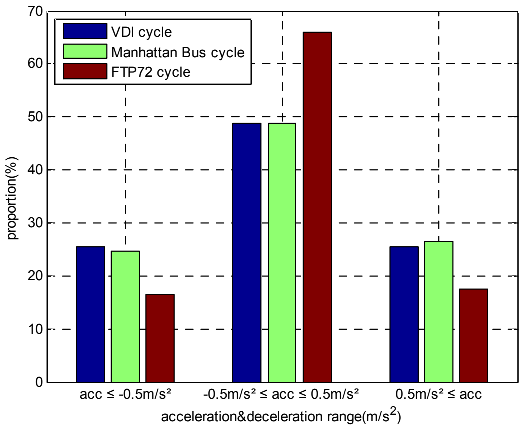

Figure 7: Proportions of acceleration and deceleration

When the forklift used hydraulic equipment, the engine was accelerated to high speed, which increased the fuel consumption. However, an assisting motor would improve engine efficiency.

With regard to the test results of the engine forklift, the effects of hybridization on the forklift are summed up in three points: 1) The forklift is driven at low speed with high torque, and it has a high inertia; 2) The forklift has a repeated pattern of speed that consists of acceleration and deceleration; 3) The engine loses much power during the working operation. These unique characteristics of the forklift decreased the fuel economy of the engine, which could be improved using a hybrid system to power the forklift.

3 Hybrid power propulsion system on forklift

3.1 Hybrid system on forklift

The hybrid propulsion system on the forklift used in this experiment is shown in Figure 8. Various hybrid configurations for use in vehicles have already been proposed [4, 5]. The hybrid configuration shown in Figure 8 is recommended in forklifts. The series hybrid type is applied to the driving part, and the parallel hybrid type is applied to the hydraulic part. This hybrid configuration is relatively simple from the point of view of mechanics. Although this hybrid system is similar to Toyota's hybrid concept, this configuration upgrades the hybridization level by increasing the battery capacity to improve driving performance. When the hybrid configuration is identical, the fuel economy depends on the level of hybridization [6].

In this hybrid configuration, a clutch is placed between the engine, generator, and transmission is also placed in the driving part. The clutch enables the use of the engine's on-off function, and the transmission improves the drive and grade ability of the forklift. Thus, this hybrid configuration is designed to enhance fuel efficiency as well as maintain the advantages of engine forklifts.

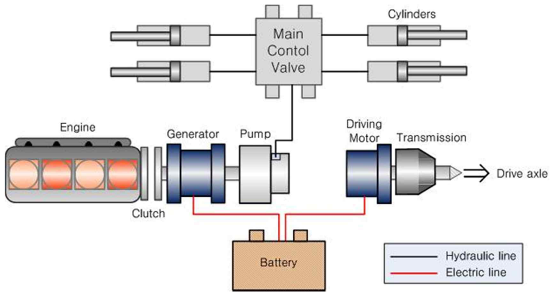

Figure 8: Hybrid propulsion system on forklift

The power flow of this hybrid propulsion is illustrated in Figure 9 and Figure 10.

When the forklift is driven, the driving motor drives the forklift and regenerates electric power by braking. The generated power by the engine-generator set and the electric power from the battery are used to drive the motor. The engine provides the generator with mechanical power, and then the generator converts the mechanical power to electric power. Because the engine is disconnected from driving motor, the engine could be operated at optimal efficiency, depending on the state of charge (SOC) in the battery.

When the forklift is handling a load, the pump converts from mechanical power to hydraulic power. Because the engine, generator, and pump are mechanically connected, the engine provides the pump mainly with mechanical power, and the generator provides optional assistance to the engine. Hence, this hydraulic power system could be called "parallel hybrid configuration."

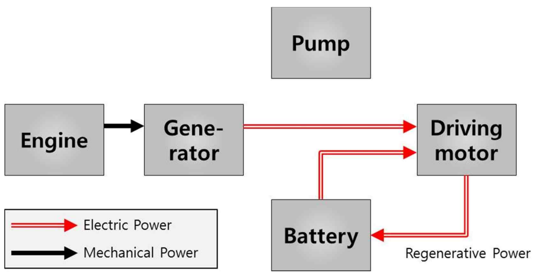

Figure 9: Power flow (driving case)

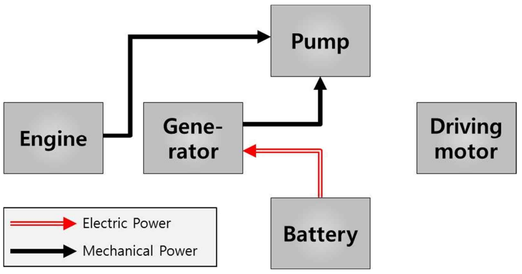

Figure 10: Power flow (load handling)

As described above, this hybrid forklift is a combined series and uses parallel hybrid configuration.

3.2 Fuel economy improvement analysis

The hybrid forklift is modeled and simulated under several conditions. In [7], which modeled and analyzed a power system in hybrid forklifts, the hybrid forklift was expected to show an improvement in fuel economy of 35%, compared to the engine forklift. This simulation assumed that the efficiency of the motor and battery was between 85% and 90%. The scaled diesel engine map in the ADVISOR program was used [8]. The optimal power distribution strategy between the engine and battery had not yet been adopted. In the present simulation, regenerative braking was used as much as possible, and the effect of engine downsizing was not considered. The simulation results are described in Figure 11 and Figure 12.

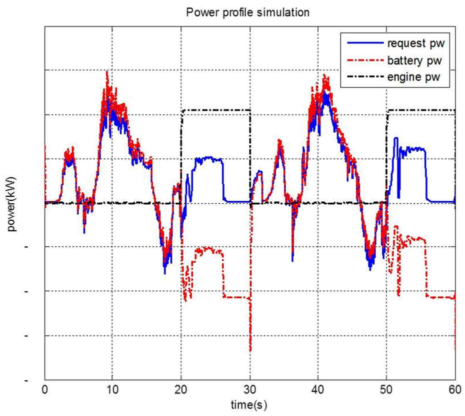

Figure 11: Results of power distribution

Figure 11 shows that a simple power distribution strategy was applied. The engine was set at 20 s and 50 s for approximately 10 seconds to generate electric power by the generator and provide the pump with mechanical power. This time was used for the load-handling operation. Because the most efficient engine power is higher than the hydraulic request power is, the engine performs the generating function and the load-handling function at the same time. When the forklift is driven, battery power is used if the SOC is sufficient. Because this operation mode is electric, it is suitable in indoor work sites for short periods. Figure 12 shows the comparison of fuel consumption between the engine forklift and the hybrid forklift. As described, fuel consumption increased sharply when electric power was generated.

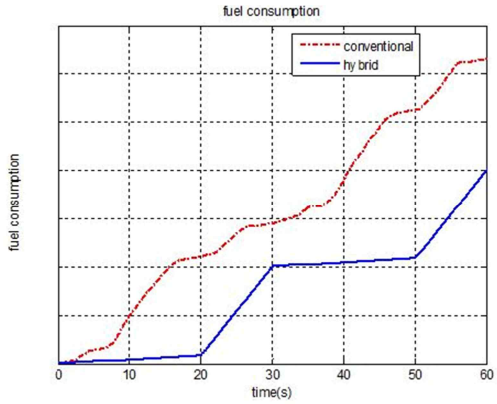

Figure 12: Comparison of fuel consumption

The improvement in fuel consumption is attributed to several points. The first major cause of improvement is that the operating engine was downsized efficiently. Figure 13 shows the operation points of the engine forklift in an engine efficiency map. In the case of engine forklifts, the maximum power of the engine is designed to cover the driving and load-handling functions. Therefore, in some engine operations, such as low speed with low torque and high speed with low torque, the engine becomes inefficient.

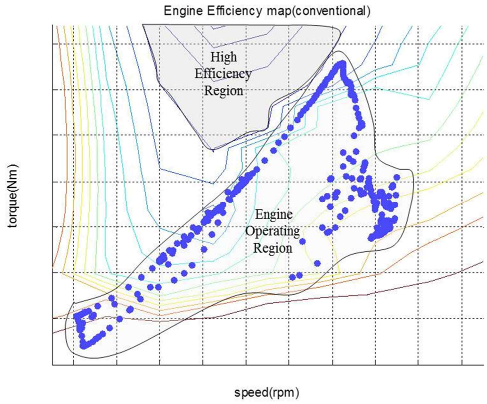

Figure 13: Engine operating region (Engine forklift)

The maximum power of the engine was downsized by 70%, compared to the existing engine in the hybrid forklift, which means that the battery compensated for the reduced engine power. Thus, the downsized engine was more efficient than the existing engine.

Moreover, there is the possibility that the engine operating point could be moved to the high efficiency region.

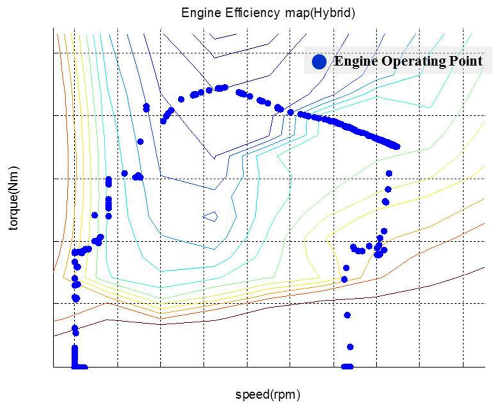

Figure 14: Engine operating region (hybrid forklift)

Figure 14 shows the engine operating region of a hybrid forklift. Although a low efficient operating point is caused by engine dynamics and pump speed constraints, many operating points are moved to the high-efficiency region. If a variable capacity pump is applied to the forklift, fuel economy is further improved.

The second cause of improvement is that power is regenerated by braking. Figure 15 shows the power profiles of a traction motor in the VDI cycle. When the hybrid forklift is decelerated, power is regenerated by a traction motor. Energy was regenerated up to 34.9% of the consumed driving energy. This is possible because forklifts have a high inertia moment and a large portion of deceleration. For example, when forklifts are converted from the reverse direction to the forward direction, many operators push the accelerator pedal with switching the gear direction.

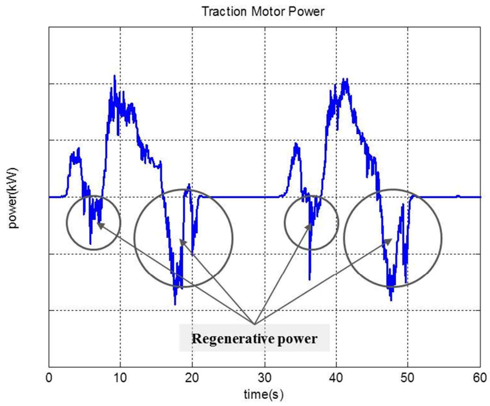

Figure 15: Power profile (Traction Motor)

In this case, there a great deal of energy was lost in the torque converter. In the hybrid system, these losses could be a source of renewable energy. The function of regenerative had a significant impact on fuel efficiency.

The third cause of improvement is highly efficient driving when the forklift speed is low and the request torque is high. Figure 16 shows the characteristics of a traction motor. The solid and dotted lines indicate continuous torque and instantaneous torque, respectively. The painted dots indicate the root mean square (RMS) of the operating points in each test cycle. The maximum torque curve is drawn from 0 rpm, which means that the traction motor takes advantage of the initial start-up of the forklift. This is a critical reason that the forklift repeats the run and stops. Furthermore, the run-and-stop operation is a main factor in decreasing fuel economy. The motor is relatively efficient in this dynamical operation. The RMS operating points of the VDI cycle and the Perkins cycle (P), which is another cycle used to test forklifts, are located in the high efficiency region of a traction motor. The energy efficiency of the forklift is improved by applying the traction motor.

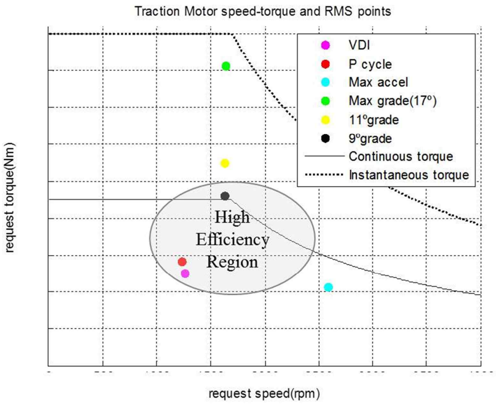

Figure 16: Characteristics of a traction motor

4 Conclusion

This paper explains the hybrid forklift system and describes an experimental simulation performed to test the efficiency of this system. It discusses the simulation results and analyzes the improvement in fuel economy. The results showed several advantages to applying the hybrid system on engine forklifts, such as its dynamical operating patterns, speed, and torque characteristics. The experiment results of the engine test showed that the engine forklift has dynamical acceleration and deceleration pattern, similar to the Manhattan bus cycle. The hybrid configuration that is appropriate for forklifts is presented. This configuration considers fuel economy, drive ability, and grade ability. This configuration is modeled and simulated. The simulation results showed an improvement in fuel economy of more than 30% compared to an engine forklift. This result was derived from the assumption that a fixed capacity pump is adopted for use in the forklift. The effects of engine downsizing and optimal power distribution on the engine and the battery are not considered. Therefore, if the hybrid configuration is optimized, the fuel economy is expected to improve by more than 30%, compared to the engine forklift. Finally, the factors of improvement in the fuel economy of the hybrid forklift are summarized in three points. The first cause is downsizing the engine and the operating engine efficiently. The second cause is regenerative braking. The third cause is the increase in driving efficiency by using a traction motor. Consequently, the use of a hybrid propulsion system on forklifts is recommended to improve fuel economy.

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