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Proposal of Power Synthesis Mechanism in Hybrid System for Compact Racing Car: A Fundamental Consideration on Structural Design and Vehicle Movement Performance

by

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Abstract

The mainstream power units in ordinary cars have begun to be replaced with hybrid units in recent years; a hybrid car has two different power sources. Many studies are being conducted on hybrid vehicles with a view to improving the fuel consumption. However, few studies have actively used the characteristics of a gasoline engine outputting high torque at high rotation speeds and an electric motor outputting high torque at low rotation speeds to improve the dynamic performance of compact cars. Therefore, this research proposes a compact and lightweight hybrid system that can be mounted on a small racing car and examines its fatigue strength. The results show that the proposed hybrid system has sufficient structural strength and is superior to a conventional hybrid system in terms of dynamic performance.

Keywords: Compact racing car, Hybrid system, Formula SAE

1. Introduction

The mainstream power units in ordinary cars begin to replace with hybrid car in recent years. A hybrid car has two different power sources; depending on the driving conditions, it is powered by a motor, an engine, or a combination of both. The hybrid car regenerates kinetic energy during deceleration and accelerates by turning an electric motor with this energy, thereby improving fuel economy. Many studies have been conducted on such commercially available hybrid vehicles[1-4]. On the other hand, there are only a few studies that have actively used the characteristics of a gasoline engine outputting high torque at high rotation speeds and an electric motor outputting high torque at low rotation speeds to improve the dynamic performance of compact cars. Among these studies, there is no research on small vehicles with limited space such as race cars.

In recent years, Formula SAE (FSAE) has developed globally, mainly in universities. Formula SAE participants compete not only for the lap times and the circuit speeds of the manufactured vehicle but also it is the educational program that is subject to the for judgment on parameters such as originality and innovation[5]. The Formula SAE competition for hybrid vehicles (Formula Hybrid) is mainly conducted in the United States. Based on the regulations of Formula Hybrid, there are many cases where the transmission is equipped with a motorcycle engine. However, the dynamic performance of a vehicle fitted with a hybrid system having an integrated engine and transmission has not been studied. Therefore, in this study, simulations were conducted to evaluate the machine performance of a hybrid system for small-sized sports vehicles, and the hybrid system design was tested on actual equipment.

2. Proposal of Driving Force Synthesizer

The powertrain system in a conventional hybrid vehicle is shown in Fig. 1. In ordinary car, planetary gears that have excellent transmission efficiencies are often used in ordinary cars. However, too heavy for use in compact cars and not suitable for FSAE vehicles, which require spatial versatility because of their compactness. Therefore, we propose the

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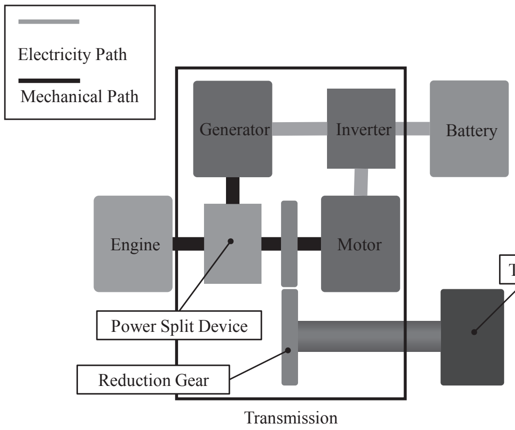
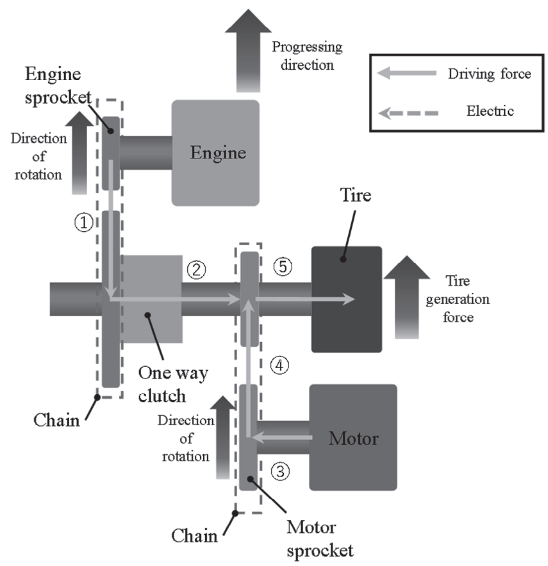
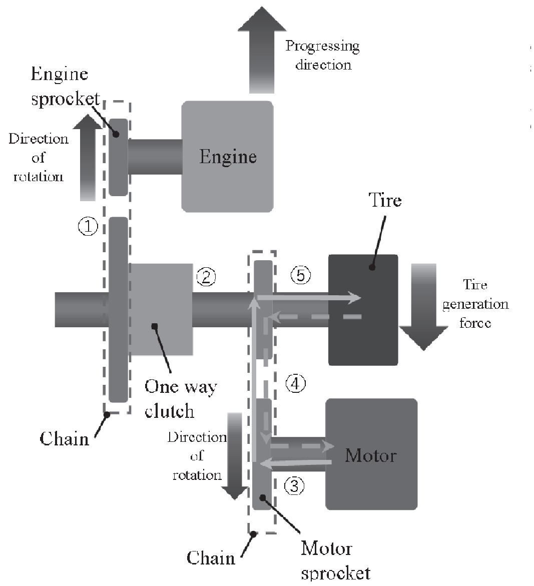


Fig. 1 Powertrain system in a conventional hybrid vehicle.



(a) Acceleration



(b) Deceleration

Fig. 2 Proposal of a device for synthesizing traction force with an engine and electric motor.

torque synthesizer shown in Fig. 2.

Figure 2 (a) shows the flow of power transmission during acceleration. First, the driving force generated from the engine sprocket is transmitted to the tire spindle side by the chain at ① and to the tire shaft via a one-way clutch at ②. Second, the driving force generated from the motor sprocket at ③ is transmitted to the tire shaft side sprocket with the chain at ④. Finally, combined driving forces from the engine and motor are transmitted to the tire at ⑤.

During deceleration, as shown in Fig. 2 (b), there is no driving force from the engine sprocket at ①, the motor driving force is not transmitted to the engine through the one-way clutch at ②, and the engine-driven sprocket on the tire shaft side idles. Then, the driving force generated from the motor sprocket at ③ is transmitted to the tire shaft side sprocket with the chain at ④and to the tire at ⑤. Because of this mechanism, it is thought that the maintenance of this system is easier than that with planetary gears.

3. Design of Hybrid System Based on The Regulation of Formula Hybrid

3.1 *Composition of hybrid system*

To evaluate the effectiveness of the proposed hybrid system on an actual vehicle, we constructed a hybrid prototype system conforming to the regulations of Formula Hybrid regulation is performed.

3.1.1 *Engine*

The rules of Formula Hybrid stipulate the use of a gasoline engine with a displacement of up to 250 cc or less or a diesel engine with a displacement of 310 cc. The engine used for the proposed hybrid system was decided according to the following conditions. The FSAE vehicle is rear-wheel-drive, and the engine is mounted on the rear side of the driver. Considering the large amount of heat generated by the engine, the cooling system is water-cooled. The engine is started with a self-starter, and the fuel injection system is electric fuel injection system. The fuel system is capable of responding to changes in altitude and weather. Furthermore, integrating a motorcycle engine with the transmission is advantageous for the weight, compactness, and output. In consideration of the availability of parts, we selected vehicles made by domestic manufacturers. The models that fulfilled the conditions are listed in Table 1. From the comparison, it was decided to use the G363E type engine of the WR250R/X because it was the best among the three in terms of the maximum output and maximum torque, and its parts were easily available. Table 2 lists detailed specifications of the G363E engine[6].

Table 1 Comparison of engines.

Vehicle name	CRF250 RALLY	WR250R/X	KLX250
Engine model number	MD38E	G363E	LX250DE
Vehicle price [yen]	648,000	721,440	574,560
Max power [PS]	24	31	24
Max torque [N·m]	23	24	21

Table 2 WR250R engine specifications.

Model	Water cooled 4 stroke DOHC Single cylinder
Engine model number	G363E
Total displacement	248 cc
Compression ratio	11.8
Inner diameter (bore)	77.0 mm
Stroke	53.6 mm
Fuel supply device	Injection
Maximum output	23 kW /10000 rpm
Maximum torque	24 N·m /8000 rpm
Mass	44 kgf

Table 3 Motor comparison table.

Model number	ME0913	AGM001
Maximum output	30 kW	30 kW
Maximum torque	90 N·m	60 N·m
Cooling method	Air cooled forced fan type	Oil / water cooling

Table 4 ME 0913 Motor specifications.

Continuous output	12 kW maximum 30 kW (DC 96 V)
Rated current	AC 125 A (motor control DC 180 A)
Mass	15.9 kg
Recommended maximum rotor speed	5000 rpm
Maximum stall torque	90 N·m
Control voltage	0 to 96 VDC input
Brush / Brushless	Brushless

3.1.2 *Electric motor*

The selection condition for the electric motor in Formula Hybrid is a brushless motor with a maximum output of 30 kW. The brushless motor does not include a brush and commutator; it was incorporated into our selection because it is almost maintenance-free because of the absence of the brush, which is a consumable item. The motors suitable for electric vehicles and satisfying this condition are comparison of each motor is shown in Table 3. In ME 0913, the maximum torque of 90 N·m is higher than that of the AGM 001, which is 60 N·m. In addition, the cooling system of ME 0913 is an air-cooling system, whereas the AGM 001 adopts oil-cooling and water-cooling system. In the case of the oil-cooled or water-cooled systems, it is necessary to provide an oil cooler and a radiator, which leads to an increase in weight; it is also conceivable that oil or water may leak when stones or small objects hit the vehicle during operation. Therefore, we decided to adopt ME 0913, which also generates higher torque and has high

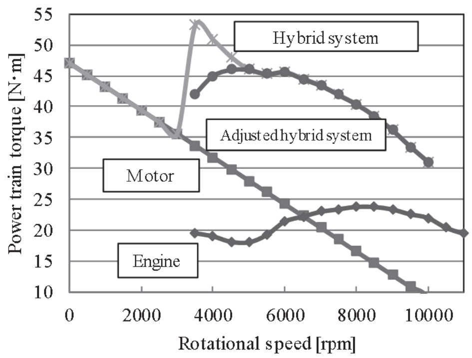


Fig. 3 Torque curve of proposed hybrid system comparison.

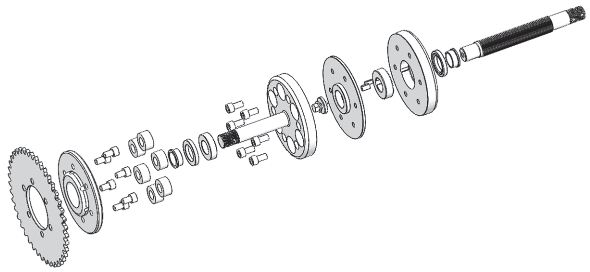
reliability. The detailed specifications of the ME 0913 type motor are listed in Table 4[7]. Figure 3 shows the torque curves of the G363E engine, ME0913 motor, hybrid system, and adjusted hybrid system according to the maximum rotation speed of the engine during deceleration.

3.2 *Torque synthesizer*

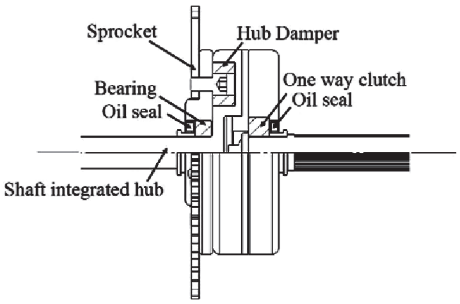
In this section, the device for synthesizing the torque of the motor and engine is designed. Since the engine operation cannot be reversed, a structure that moves the engine in one direction is necessary. In generally, the mainstream of the engine and motor synchronization method of the FSAE hybrid system is a planetary gear mechanism[8-10]. In contrast, the proposed torque synthesizer is used a motorcycle chain for power transmission from the engine to the drive shaft, and the cam clutch is installed on the drive shaft to move it in one direction. The proposed torque synthesizer that the high-strength cam clutch and the hub damper are built in the integral shaft has versatility that it can be installed to various power units. Though, other researchers proposed a power train system consisted of two motors, an electric motor for acceleration and regeneration, there is a problem of weight increase. However, our proposed system can drive one electric motor for acceleration and regeneration. This is advantage and originality of the proposed system. However, there is a disadvantage for compactness comparing the planetary gear mechanism and proposed system. In the view point of vehicle layout, it is necessary to secure the chain space. Although, time loss of stretching a loose chain occurs, it sought to be suppressed in terms viewed from the about 0.1 second or less delay in acceleration performance as the time of the driving lag.

3.2.1 *Cam clutch*

Selection criteria for the cam clutch involve the following three points. First, it can withstand a large torque fluctuation from the chain mechanism. Second, it is easy to replace when broken. Finally, it does not reverse rotation easily when a force is applied in a direction opposite to the meshing direction.



(a) Configuration of designed torque synthesizer



(b) Front view of assembled torque synthesizer

Fig. 4 Drawings of designed torque synthesizer.

Within the scope of conditions during running, the engine generated a maximum torque of 24 N·m, the decelerated motor generated 30 N·m, and the combined torque acted on the cam clutch. The allowable shearing stress of the cam clutch was 61 N·m. Therefore, BB20-2K-K[11], which meets all the above conditions, was selected.

3.2.2 *Drive gear*

A one-way mechanism operates on the engine side, and a motorcycle sprocket is used. The chain size was selected to be 520, considering friction.

3.2.3 *Buffer material*

There have been situations in the FSAE where large breaks have occurred in the differential cases because of the absence of cushioning material on the shafts. Therefore, shock absorption is necessary during vehicle operation to reduce the impact of torque fluctuations from the chain mechanism. Thus, a hub damper[12] for a galespeed motorcycle made of a cylindrical active was selected for its ease of design.

3.2.4 *Shaft integrated hub*

Based on the specifications determined in subsections 3.2.1 to 3.2.3, we designed a shaft integrated hub. Because the torque from the engine and motor is transmitted to the tire through this hub, it is necessary to determine an appropriate shaft diameter that can withstand damage caused by the total torque. The shaft diameter d is derived as follows.

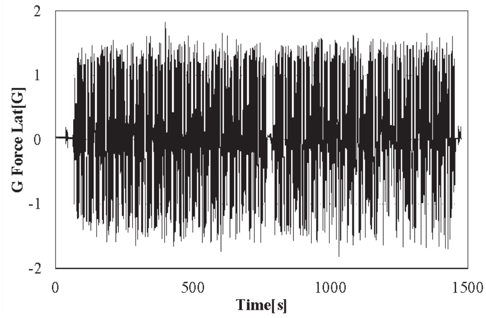


Fig. 5 Time history of the acceleration sensor in the longitudinal direction.

$$d = \sqrt[3]{\frac{S\left(i_E T_E + i_M T_M\right)}{\pi\tau}} \qquad (1)$$

where T_E is the shaft torque of the engine [N·m], T_M is the shaft torque of the motor [N·m], i_E is the reduction ratio of the engine side transmission mechanism, i_M is the reduction ratio of the motor side transmission mechanism, τ-ratio by the motor side transmission mechanism, τ is the allowable shear stress [Pa], and S is the safety factor. T_E is 24.0 N·m, T_M is 90.0 N·m, i_E is 1.00, i_M is 0.333, τ is 450 MPa, and S is 15. From Eq. (1), the shaft diameter d was obtained as 21.8 mm; the bearing specification was taken into consideration and d was set to 25 mm. Fig. 4 shows a schematic diagram of a driving-force synthesizing mechanism designed with the specifications determined according to 3.2.1 to 3.2.4.

4. Allowable Fatigue Life of Proposed Hybrid System

4.1 *Allowable lifetime of shaft integrated hub*

In the endurance competition that runs the longest distance among dynamic events, the intensity calculation is a static condition, and we examined whether it is acceptable for an impact load during acceleration/deceleration. Fig. 5 shows the time history of the acceleration sensor in the longitudinal direction when the FSAE vehicle was operated. From this figure, we see that acceleration/deceleration is performed 857 times for a travel distance [5] of about 1 km. The total travel distance of the manufactured vehicle is about 600 km from the shakedown to the end of the competition. It can thus be estimated that the total number of acceleration/deceleration cycles undergone by the vehicle when traveling 600 km in the endurance event is about 500,000 times in the endurance event in Fig. 5.

4.2 *Fatigue structure analysis*

The allowable lifetime of the hybrid system is derived as mentioned above. Therefore, we analyze the shaft integrated hub of the torque synthesizer with the driving torque applied

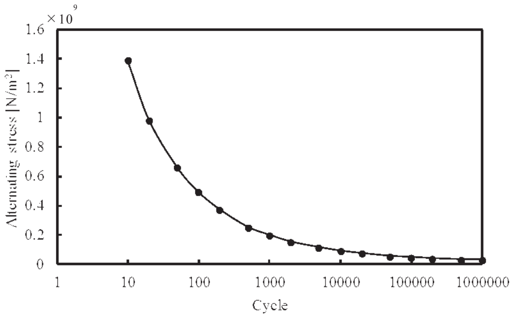
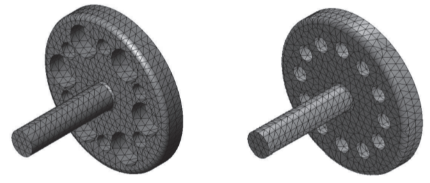
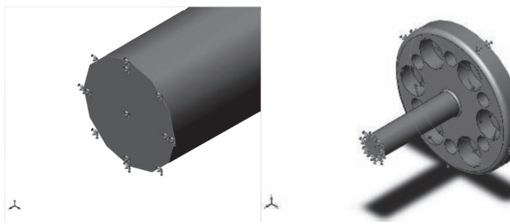


Fig. 6 Fatigue SN diagram of SS400.



(a) Without damper (b) With damper

Fig. 7 Analytical model of the shaft integrated hub.



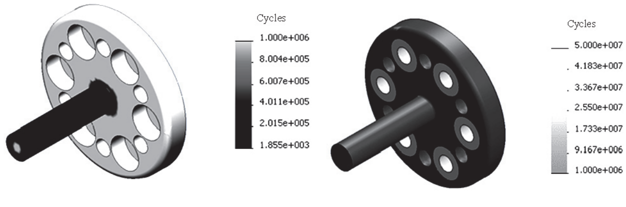
(a) Acceleration (b) Deceleration

Fig. 8 Fixed conditions in fatigue structure analysis.

by the engine and motor. Fig. 6 shows the fatigue SN diagram of SS400, which is a material. Fig. 7 shows the analytical model of the shaft integrated hub. In the figure, (a) shows the case where the damper is not installed and (b) shows the case where the damper is installed on the hub. We consider the case where stress is applied to the shaft part by sudden braking and the case where stress is applied to the part holding the damper by rapid acceleration. The fixed conditions during acceleration are shown in Fig. 8 (a), and the fixed conditions during deceleration are shown in Fig. 8 (b).

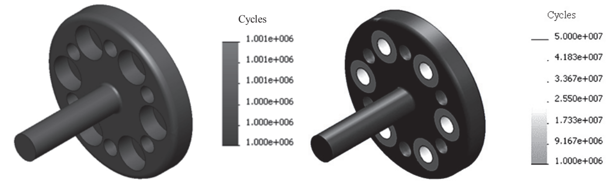
4.3 *Analysis result*

Figures 9 and 10 show the comparison of the analysis results in the case of acceleration and deceleration, respectively. In each figure, (a) shows the analysis when the damper is not installed and (b) shows the analysis when the damper is installed. Compared with the state without the hub damper, the minimum life of the outer flange shaft part increased by about 1000 cycles and a lifetime of 1.0×10^6 cycles was obtained for the state with the damper. In addition, although the minimum life span of the damper part did not change, the maximum life expectancy increased from 4.9×10^7 cycles to 5.0×10^7 cycles.



(a) Without damper (b) With damper

Fig. 9 Result of fatigue analysis in the case of acceleration.



(a) Without damper (b) With damper

Fig. 10 Result of fatigue analysis in the case of deceleration.

Table 5 Vehicle data of proposed torque synthesizer and planetary gear.

General Data			Engine Data		
Mass [kg]	Torque synthesizer	340	Thermal Efficiency [%]		35
	Planetary gear	369.7	Transmission Data		
Driven Type		2WD	Gear 1		2.642
Aera Data			Gear 2		1.812
Drag Coefficient		0.8	Gear 3		1.318
Downforce Coefficient		1.2	Gear 4		1.04
Front Area [m^2]		1.1	Gear 5		0.888
Air Densuty [kg/m^3]		1.226	Gear 6		0.785
Tire Data			Final Drive Ratio		3.145
Tire Radius [m]		0.128	Drive Efficiency [%]	Torque synthesizer	83
Rolling Resistance		0.03		Planetary gear	85
Longitudinal Friction		1.4			
Lateral Friction		1.5			

5. Creation of Experimental Equipment

In order to evaluate the effectiveness of the proposed hybrid system, runtime simulations were carried out by mounting the system on moving vehicles. The simulation software Optimumlap was used for running performance analyses as this is the same software used by Formula SAE[12)]. The parameters of each vehicle are shown in Table 5. When planetary gears are used, the weight of the system increases by about 25 kg compared with that with the driving force synthesizer. Since the driving force transmission efficiency of the chain is 92 to 96% and the transmission efficiency of the planetary gear is 92 to 94%[13,14)], the transmission efficiency is set to 83% for the vehicle using planetary gears. In order to analyze the basic driving performance, the running course was assumed to be elliptical. There are three types of travel courses used for FSAE hybrid competitions in the USA;

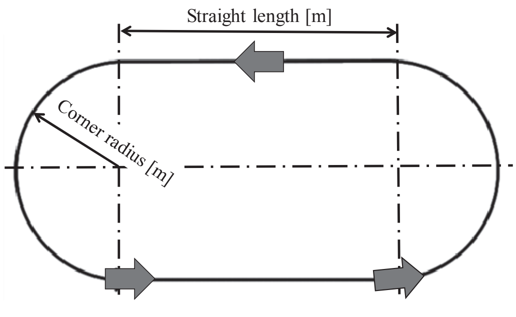


Fig. 11 Schematic of oval course in simulator.

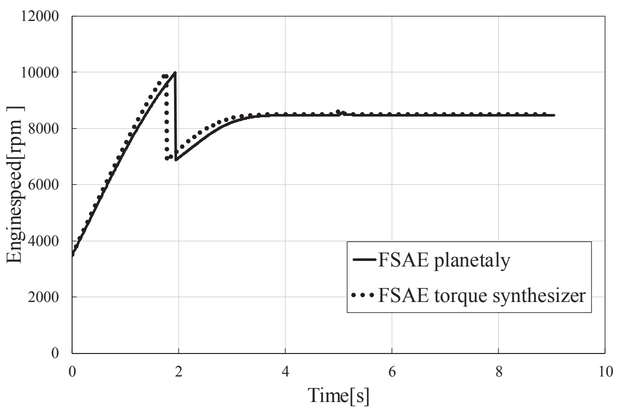


Fig. 12 Comparison of analytical result between proposed system and planetaly gear (the straight length is 2 m and the corner radius is 25 m).

Table 6 Analytical results with hybrid system on oval course.

Straight length [m]	Coner radius [m]	Time [s]	
		Synthesizer	Planetarygear
2	25	8.94	9.04
	80	18.12	18.66
	120	25.27	25.95
	185	36.76	37.61
3	25	9.04	9.14
	80	18.18	18.72
	120	25.33	26.01
	185	36.82	37.66
60	25	14.25	14.44
	80	21.44	22.04
	120	28.54	29.27
	185	40.02	40.91

the straight lengths are 2 m, 3 m, and 60 m; and the corner radii are 25 m, 80 m, 120 m, and 185 m. By combining these conditions, an elliptical course as shown in Fig. 11 was set and lap times for one round of each of the 12 types of travel courses were compared.

Figure 12 shows the analyses of the rotation speed when the straight length is 2 m and corner radius is 25 m. It was confirmed that the vehicle equipped with the proposed torque synthesizer is able to shift up 0.2 s earlier, and the acceleration performance is also proportionally improved. The simulation results under all the conditions are listed in Table 6. It was confirmed that the proposed hybrid system improved the running performance of the vehicle under most conditions.

Furthermore, we conducted an F-test and a t-test to evaluate the results numerically. Since $P = 0.2814 > 0.05$ for the F test, it can be said that there is no difference in data dispersion between the planetary gear vehicle and the proposed torque synthesizer vehicle at the significance level of 5%; the t test revealed that $P < 0.05$ and there was a significant difference. From the analytical condition as shown in table 5, the mass of vehicle proposed torque synthesizer is set to be 30 kg lighter than the planetary gear vehicle, and the drive efficiency is set to be 2% lower than the planetary gear vehicle. From the analytical results, it is considered that the factor of improving the dynamic performance is weight reduction by installing the proposed torque synthesizer. Thus, the numerical evaluation of the torque synthesizer was completed.

6. Conclusion

In this research, we proposed a new hybrid system for compact race cars with a focus on improving the motor performance. We proposed a mechanism for synthesizing torque with a motorcycle engine that was integrated with a transmission and an air-cooled motor by a chain and sprocket; it was possible to construct a system that was lightweight and had high flexibility with regard to its layout. Next, we designed the proposed hybrid system according to the regulations of Formula Hybrid. It is clear from the fatigue analysis by the finite difference method that the system has sufficient strength to operate from the shakedown until the end of the competition. We also demonstrated improvement in motor performance with the proposed system by running simulations alongside a conventional system. As a future works, we will confirm the performance of only engine and electric motor, before performance of combined system. Furthermore, we will install the proposed hybrid system on actual experimental vehicle, and confirm the behavior characteristics, safety and maintenance of the vehicle.

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