技術論文

Hybrid Electric Two-Wheeled Vehicle Fitted with an EVT System（Electrical Variable Transmission System）

Hideki Furuta　Jun Yoshida

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要旨

近年、地球温暖化や化石燃料の枯渇、大気汚染の回避が重要視されており、二酸化炭素排出量を削減できる環境にやさしい二輪車が求められている。一方、二輪車においては、ドライブトレインの小型化・軽量化・長距離走行など、これまで通りお客さまの期待に応える必要がある。このような背景の中で、ハイブリッド電動自動車（HEV）のシステムは、環境にやさしいパワートレインを実現するための最も現実的な手段であり普及しているシステムである。

本研究では、これらの要求に応え、燃費向上と駆動系のコンパクト化を実現する全く新しい電子式トランスミッションであるEVT（Electrical Variable Transmission）システムを搭載したハイブリッド電動二輪車を紹介する。EVTシステムは、ステータ内に取り付けられたダブルローターのセットで構成されている。EVTシステムを搭載したハイブリッド電動二輪車は、純電動自動車としての電動駆動機能と回生制動機能、エンジン発電機としての内燃機関始動機能と発電機能、それらを統合制御によって組み合わせた発電と駆動を含むハイブリッド電動機能を備えている。また、EVTシステムは、ブーストアクセラレーション機能やダブルローターの直結機能を実現できるため、従来のバイクに対して幅広いメリットと独自の新しい価値を提供することが可能である。

筆者らは、この独自の電動トランスミッションEVTを搭載したハイブリッド電動二輪車のプロトタイプを開発した。

本稿では二輪車に対して検討を行い、ハイブリッドトポロジー、EVTの多彩な機能、EVTの動作原理、EVTと二輪車のレイアウト構成、試作EVTマシーン紹介、EVTパワートレインハイブリッド制御戦略、ハイブリッドパワートレイン開発環境、ハイブリッド電動二輪車の性能測定結果、ハイブリッド電動二輪車の可能性について考察する。

Abstract

In recent years, global warming, depletion of fossil fuels, and reducing pollution have become increasingly prominent issues, resulting in demand for environmentally-friendly two-wheeled vehicles capable of reducing CO2 emissions. However, it remains necessary to meet customers' expectations by providing smaller drivetrains, lighter vehicles, and support for long-distance riding, among other characteristics. In the face of this situation, hybrid electric vehicle（HEV）systems are considered to be the most realistic method for creating environmentally-friendly powertrains and are widely used.

This research introduces a hybrid electric two-wheeled vehicle fitted with an electrical variable transmission（EVT）system, a completely new type of electrical transmission that meets the aforementioned needs, achieving enhanced fuel efficiency with a compact drivetrain. The EVT system comprises double rotors installed inside the stator. The hybrid electric two-wheeled vehicle equipped with the EVT system has the electric drive and regenerative braking functions of a fully electric vehicle, internal combustion start and power generation functions as an engine generator, and hybrid power generation functions, including combined power generation and drive through integrated control. The EVT system also provides boost acceleration functions and direct double rotor connection functions, offering wide-ranging advantages compared to conventional motorcycles and enabling the provision of new types of distinctive value.

The authors developed a prototype hybrid electric two-wheeled vehicle fitted with this unique EVT electrical transmission. This article considers its qualities compared to other two-wheeled vehicles and describes the hybrid topology, the various functions of the EVT, the working principle of the EVT, the EVT configuration and the two-wheeled vehicle configuration, the prototype EVT machine, the EVT powertrain hybrid control strategy, the hybrid powertrain development environment, the results of hybrid electric two-wheeled vehicle performance measurements and the possibilities presented by hybrid electric two-wheeled vehicles.

1 INTRODUCTION

In recent years, global warming and the depletion of fossil fuels have seen growing interest in sustainable, pollution-free vehicles. Based on agreements such as those at the UN Climate Change Conference (COP), regulations to reduce CO_2 emissions are gathering pace and research and development into environmental and fuel-efficient technologies that can satisfy future automobile and two-wheeled vehicle fuel efficiency regulations is taking place around the world. In terms of four-wheeled automobiles, electric and hybrid electric vehicles are known to be effective ways to accomplish these tasks. Similarly, improving energy conversion efficiency is also considered important in the case of smaller-scale mobility, as typified by two-wheeled vehicles.

The authors carried out research and development on a hybrid electric two-wheeled vehicle capable of addressing three existing customer needs, ensuring sufficient riding distance, alleviating the inconvenience of insufficient charging infrastructure and reducing the high cost of batteries. The authors aimed for high fuel efficiency targets in order to achieve significant improvements in fuel efficiency relative to conventional two-wheeled vehicles, compared to those achieved with two-wheeled vehicles equipped only with conventional ICEs.

Systems equipped only with conventional ICEs require a trade-off in terms of reduced acceleration and maneuverability in order to achieve high fuel efficiency targets. The authors carried out research and development on a new powertrain capable of resolving this trade-off.

In general, fully electric two-wheeled vehicles are often fitted with expensive batteries, thereby increasing the cost of the vehicle. Hybrid electric vehicles, on the other hand, offer a means of propulsion that can lower end user costs compared to fully electric vehicles because they minimize use of expensive batteries. However, this tends to increase costs compared to vehicles equipped only with conventional ICE. Hybrid powertrain units used in standard four-wheeled vehicles up to this point have tended to be expensive and lead to increases in size and weight. Against this background, the fitting of relatively low-cost hybrid electric powertrains to two-wheeled vehicles was challenging. The authors have developed a completely new hybrid system that can be fitted on vehicles from small scooters to two-wheeled vehicles and surpasses the structure, configuration, functions, and performance of conventional hybrid systems, together with a new hybrid electric two-wheeled vehicle fitted with this system. The hybrid electric two-wheeled vehicle in this research can achieve both low fuel consumption and provide new sensations, such as quietness and acceleration unique to electric vehicles, compared to conventional vehicles fitted with ICEs.

The authors selected a 125 cc scooter as the subject for research and development.

One reason for this selection was that, when taken as a whole, the large scale of global production makes it a vehicle category connected to a large quantity of carbon dioxide emissions. This is illustrated by the fact that 5 kW to 15 kW (100 to 200 cc) scooters account for a large proportion of the total number of two-wheeled vehicles produced worldwide. As a result, significantly reducing carbon dioxide emissions in this vehicle category has the potential to have a major impact on future global warming.

Another reason behind the vehicle selection was that installing hybrid system parts in the limited space available on a small scooter provided an opportunity to gain an understanding of the potential of EVT systems in terms of being compact and lightweight. The construction of hybrid systems requires additional components, such as drive motors, generators, inverters, and lithium-ion batteries. The authors believed that installing a hybrid system on a small scooter with a limited mounting space with the aim of creating an innovative powertrain had the potential to enable mitigation of global warming in a wide range of two-wheeled vehicle categories.

Innovative compact, lightweight hybrid systems also have the potential for future application in marine, agricultural, and general-purpose equipment in addition to two-wheeled vehicles, supporting further efforts to reduce global warming.

The base scooter and ICE specifications of the 125 cc scooter that is the subject of this research are shown in Figure 1.

For the ICE, a unit-swing type powertrain equipped with a mass-produced 125 cc forced air-cooled single-cylinder ICE was used.

Length (mm)	Width (mm)	height (mm)	WheelBase (mm)	Vehicle weight (kg)	Engine type	cylinder array	Cooling method
1820	685	1145	1280	99	4stroke	Single	air cooling
Displacement (cc)	Bore (mm)	Stroke (mm)	Compression ratio	Max Power (kW)	Max Torque (Nm)	Max Speed (rpm)	Fuel tank (L)
124	52.4	57.9	11	5.7 (6500rpm)	9.4 (5000rpm)	7500rpm	4.4

Fig. 1 Base Scooter and ICE Specifications Used for Research

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TWO-WHEELED VEHICLE AND HYBRID TOPOLOGIES

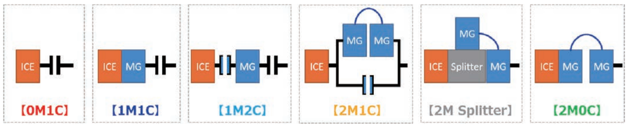

Fig. 2 Hybrid System Topologies
(0M1C: BASE, ICE: Engine, MG: Motor Generator, M: Traction Motor, C: Clutch, Splitter: Power Splitter)

As shown in Figure 2, there are generally three topologies of hybrid system. These topologies are: series topologies (2M0C: series hybrids), parallel topologies (1M1C, 1M2C: parallel hybrids), and series/parallel topologies (2M1C: series/parallel switchable hybrids, 2M Splitter: power split type with mechanical planetary gear set). Through previous research and development, it is known that series/parallel topologies generally achieve the lowest fuel consumption rate over a wide range of speeds. In addition, series topology hybrids enable independent drivetrain and ICE operation because they are not subject to motion condition restrictions related to mechanical shaft fastening structures. As a result, the ICE can operate at the most efficient operating points, thereby increasing drivetrain efficiency.

The authors carried out research and development on a hybrid powertrain with the objective of creating a two-wheeled vehicle that consumes as little fuel as possible. A desk study was conducted by applying the three aforementioned topologies to five notable types of hybrid system that have been put into practical use in the automobile market. Specifically, fuel consumption rates were examined in World Motorcycle Test Cycle (WMTC) mode, which is used as an international standard for motorcycles and includes elements such as starting, accelerating and stopping, and desk studies covering cost, vehicle weight with the system equipped and fuel consumption during high-speed riding were carried out.

Cost, in particular, is a crucial element in enabling more users to enjoy the same performance and excitement found with previous two-wheeled vehicles. The price of lithium batteries continues to rise, meaning that fitting a battery significantly increases costs. Two-wheeled vehicles equipped with hybrid systems minimize costs compared to fully battery-powered two-wheeled vehicles, however, they have the side effect of emitting greenhouse gases. At the same time, hybrid electric two-wheeled vehicles can have significantly smaller battery packs than fully battery-powered two-wheeled vehicles. In other words, hybrid electric two-wheeled vehicles can be expected to offer the market a lower-cost option compared to fully battery-powered two-wheeled vehicles. Furthermore, two-wheeled vehicles equipped with hybrid systems are significantly more efficient than conventional two-wheeled vehicles because they can operate in both a fully electric mode and a regenerative mode using the drive motor.

In addition, vehicle weight with the system equipped is a crucial design element that affects operability by a human driver because two-wheeled vehicles maneuver by tilting left and right. Operational input by shifting body weight is generally a characteristic of two-wheeled vehicles. Unnecessarily increasing the weight of a two-wheeled vehicle must therefore be avoided wherever possible because of the impact it has on convenience, the joy of riding, and human-machine sensibility (technology that creates joy and excitement for people by integrating people and machines on a high level). The left-right and front-rear balance is also important in two-wheeled vehicles because it is closely related to steering stability. For this reason, hybrid systems that are as small and light as possible are desirable.

Fuel efficiency during high-speed riding is an important element for two-wheeled vehicles because it is required when they are used as a means of transportation between cities and for long-distance touring. In addition, because two-wheeled vehicles are used to travel long distances, there is also strong demand for long cruising ranges. Unlike fully electric two-wheeled vehicles, two-wheeled vehicles with hybrid systems charge the battery while driving, providing the significant advantage of making it possible to minimize time lost due to charging when compared to fully electric vehicles.

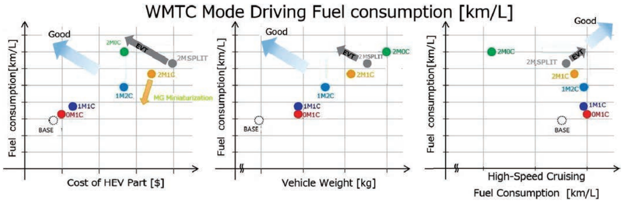

Fig. 3 Results of Study on Hybrid Topologies in Hybrid Electric Two-wheeled Vehicles

The authors carried out evaluation on the base-specification scooter through numerical calculation and carried out a desk study on the feasibility of hybrid systems.

As a result, the characteristics of each hybrid topology were clarified as shown in Figure 3. The findings shown in Figure 3 are as follows. The 1M1C (cell dynamo-type mild hybrid electric two-wheeled vehicle) currently on the market is a direct evolution from a two-wheeled vehicle equipped with ICE only and, while it offers excellent cost effectiveness, there is a limit to improvements in fuel efficiency. The 2M0C (series hybrid) can be considered an extremely effective hybrid system for two-wheeled vehicles, especially because it excels in terms of mode fuel efficiency. This is because the cost is lower than that of 1M2C/2M1C/2M power splits and fuel consumption during mode riding is low. In addition, 2M0C has a simpler structure than 1M2C/2M1C/2M power splits, and the generator and drive motor systems are completely independent. For this reason, there is a strong possibility that it will be possible to use rear wheel drive systems with battery-powered electric two-wheeled vehicles in the future. However, proceeding with the study while optimizing component specifications using numerical calculation modeling showed that it was challenging to improve fuel efficiency during high-speed driving with this system. Two-wheeled vehicle ICEs are generally of a high-speed specification, and the rotation speed of the generator motor and drive motor reaches 6,000 to 10,000 rpm, or more, during high-speed riding. This is because, in this high rotational speed region, a field-weakening current (Id) must be applied to the generator motor and drive motor. Due to this field-weakening current, it was found that copper loss and iron loss at high rotational speed reduce powertrain efficiency. While 2M0C has disadvantages, if it is applied to two-wheeled vehicles with sufficient understanding of this loss generation in high-speed regions, it can be considered a hybrid system with benefits that merit consideration of future development.

When similar studies were conducted on the other topologies, 1M2C was found to have the same cost as 2M0C, but without excellent mode fuel economy. However, the high-speed fuel consumption is excellent. 2M1C is upward compatible with 1M2C, but has higher costs than 1M2C. Of these, 2M Splitter (power split) was found to be upward compatible with 2M1C and achieve higher performance. However, 2M power splits use planetary gears, making them more expensive and heavier than 2M1C for two-wheeled vehicles.

As described above, the authors carried out a desk feasibility study, and concluded that the two specifications shown below are appropriate for hybrid electric two-wheeled vehicles.

- 2M0C is compatible with fully-electric vehicles, making it effective and giving it high future potential.
- 2M power splits and 2M1C have overall upward compatibility and high drivetrain efficiency, making them suitable for two-wheeled vehicles.

In this research and development, powertrain efficiency was given highest priority, and the 2M Splitter (power split), was selected. In addition, an EVT system that does not use a mechanical planetary gearset was selected for the 2M Splitter (power split). It was determined that EVT systems have room for growth in terms of improved fuel efficiency, cost reduction, and weight reduction in relation to hybrid electric two-wheeled vehicles.

Eliminating mechanical planetary gearsets enables EVTs to reduce costs and weight compared to 2M Splitters (power distribution) with mechanical planetary gearsets. Mechanical friction is also reduced because EVT power uses magnetic coupling for transmission. In addition, as is explained in the section on EVT operating principles, iron loss during operation is also reduced, resulting in unparalleled high transmission efficiency in the powertrain. In the feasibility confirmation performed by the authors, it was determined that EVTs are an extremely effective hybrid powertrain system for hybrid electric two-wheeled vehicles, and the authors proceeded to production.

The authors determined that 2M0C was also effective, and carried out production following evaluation. 2M0C is a series hybrid system. It was selected because is it compatible with fully electric two-wheeled vehicles and drive motors, and can be expected to have possible applications in a wide range of categories and industrial fields.

This paper principally contains explanations of the unique EVT system and comparisons of vehicle performance against series hybrids. Fuel efficiency was a particularly important point of comparison.

3 EVT FUNCTIONS ON TWO-WHEELED VEHICLES

The electrical variable transmission (EVT) configuration used as the powertrain system in the hybrid electric two-wheeled vehicle in the course of this research and development is shown in Figure 4.

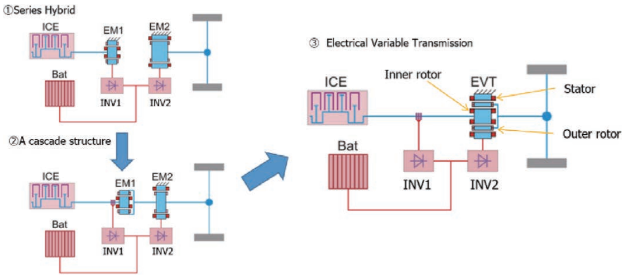

Fig. 4 Electrical Variable Transmission (EVT) Configuration and Explanation

Between 2004 and 2010, M.J. Hoeijmakers (Delft University of Technology) and Salem Mourad (TNO, Business Unit Automotive) conducted basic research on the working principle and structure of EVTs, and methods for implementation in vehicles. The basic principles of EVT are not described in detail in this paper. The principles of EVT technology are described in cited references ([1], [2] and [3]). In terms of technology to improve EVT efficiency, M.J. Hoeijmakers is known to have a patent (WO2012/018253 A1 Title: Rotating Electromechanical Converter (09.02.2012)) whereby a DC winding wire is mounted on the outer rotor in order to improve the efficiency and flexibility of the power split machine. (See Fig. 6 for information regarding the DC winding.)

Figure 4 is commonly used in understanding the operating principles of EVT. Figure 4-① shows a series hybrid. Figure 4-② shows a cascade structure. Figure 4-② has a structure whereby the outer part (EM1) and the inner part (EM2) from Figure 4-① are cascaded. Figure 4-③ shows an EVT. Figure 4-③ has a structure that integrates the outer part (EM1) and inner part (EM2) of

Figure 4-②. Understanding Figure 4-①, ② and ③ in sequence leads to an understanding of the rationality and simplicity of the EVT structure. In this research, the authors shall proceed to provide an explanation based on the aforementioned research results. The EVT includes a set of double rotors mounted inside the stator, as shown in Figure 4-③ and Figure 6. In addition to functioning as a normal electric traction motor, it also functions as a power splitter and can transmit mechanical power while changing speed as a continuously variable transmission from when the vehicle is stopped. The EVT is a power-split hybrid powertrain that does not have a mechanical gear train. Hybrid functions that can be achieved with EVTs are shown in Figure 5.

Figure 5-① shows how power splitting of engine torque can be performed as a continuously variable transmission. Figure 5-② shows how engine power can be transmitted as a clutch using magnetic couplings. Figure 5-③ shows that boost is possible during acceleration. This also means thermal efficiency can be improved by using a low-output ICE to increase the load factor, and the lack of output from a small ICE can be compensated for. Figure 5-④ shows functions as an engine generator. Driving energy can also be recovered, improving powertrain efficiency compared to current ICEs. The strength of deceleration can also be set to fit the user’s preference by controlling the regenerative power, enabling the provision of new value. Figure 5-⑤ shows that fully-electric driving without emitting exhaust gas can be achieved. In other words, the brake specific fuel consumption (BSFC) of the engine is high and the engine can be stopped completely in low efficiency regions. Figure 5-⑥ shows that reverse motion is possible. This offers new value compared to conventional two-wheeled vehicles. Figure 5-⑦ shows that the engine can be reliably started. Figure 5-⑧ shows the richness of the EVTs functions, and shows that, even if the battery SOC drops, reversing is possible by using the ICE power.

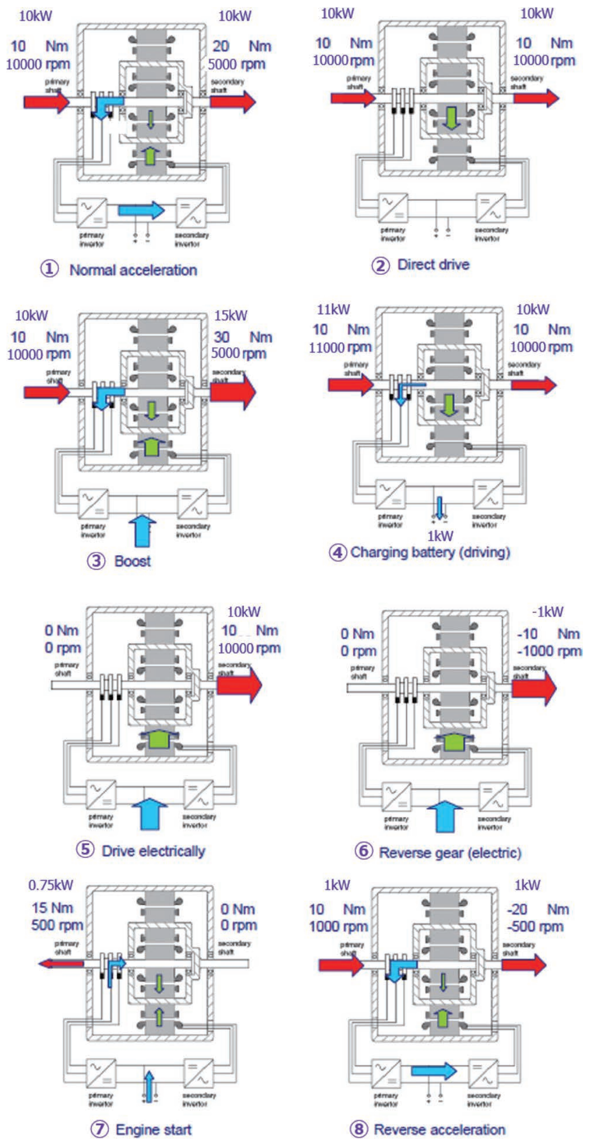

Fig. 5 EVT Hybrid Functions

4 WORKING PRINCIPLE OF PROTOTYPE EVT

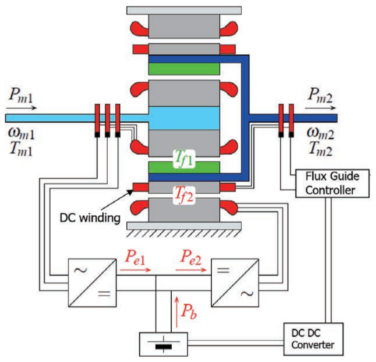

Fig. 6 Detailed Structural Diagram of Prototype EVT
(A configuration with a DC winding on the outer rotor section has been adopted in order to improve efficiency compared to the EVT shown in Figure 4-③.)

The EVT structure is shown in Figure 6. Inside the air gap inside the EVT machine, there is an inner rotor with three-phase windings, which can create a rotating magnetic field. This can be generated through the mutual relationship through the electrical (AC current) and the mechanical. Next, the mechanical rotational speed of the inner rotor is added as the electrical angular velocity of the AC current. The permanent magnet ties to follow this rotating magnetic field, and the outer rotor begins to rotate. The angle between the magnetic axis of the rotating magnetic field of the inner rotor and the magnetic axis of the permanent magnet should be kept constant, and the torque between the inner rotor and the outer rotor should be the sine of that angle (normal permanent magnet electric motor operation). The torque of this air gap acts on the outer rotor (output shaft) and the inner rotor (input shaft) in the opposite direction. The same can also be said of the outer air gap. In that case, a rotating magnetic field is generated by the stator. The rotational speed can only be controlled by controlling the stator current frequency.

The following section contains a description of the EVT magnetic circuit design. The magnetic field lines of the EVT can be seen in Figure 7. Here, there is no electrical current in the EVT. The magnetic flux lines are generated by a permanent magnet (56a in Figure 7). The inner rotor has high magnetic flux density, and a large number of magnetic field lines can be seen in a small area. In the stator, the low number of magnetic flux lines indicates low magnetic flux density The latter is because most of the magnetic flux generated by the permanent magnet flows from one pole of the magnet to the other pole of the other magnet through the iron of the outer rotor (in area 62 of Figure 7, the magnetic flux density appears low based on the plot, but is actually extremely high).

In EVTs, DC winding wires are wound on the outside of the outer rotor to improve their efficiency. (The DC winding on the outer rotor section is shown at 60a in Figure 7.) When this DC winding (field coil 60a in Figure 7) is used and an appropriate current is applied through flux guide control (see Figure 8), the magnetic flux flowing through area 62 in Figure 8 instead goes through the stator. This makes it possible to control the magnetic circuit route in the EVT magnetic circuit and the extent of the magnetic flux of the permanent magnet. This can be used to try and improve efficiency. The following section explains why EVT is suitable for use in hybrid electric two-wheeled vehicles, with reference to the aforementioned EVT magnetic circuit design concept.

Internal combustion engines (ICEs) are attached to the inner rotor and the wheels are attached to the outer rotor. The flux guide control through the DC winding (field coil 60a in Figure 7) described above plays a functional role in that it helps to minimize loss. A significant amount of the loss in electric motors comes from copper loss (related to the required current/amount of torque) and iron loss (related to speed).

The speed of a vehicle while driving at the vehicle's typical cruising speed or on the highway can be considered to be constant. The ICE normally supplies mechanical shaft power to the vehicle and provides rotation (during long-distance driving, etc.) Through design with an appropriate gear ratio between the vehicle powertrain and the EVT, the ICE rotational speed (the inner rotor rotational speed) can be matched to the rotational speed of the outer rotor, which is rotated through the gear train from the wheel speed. (The inner rotor and outer rotor can maintain the same speed relative to the typical cruising speed of the vehicle.)

Because the rotational speeds of the inner and outer rotors are the same, the frequency of the magnetic field in the inner rotor must be zero in order to maintain a constant angle between the magnetic axis of the permanent magnet and the magnetic field generated by the three-phase winding.

$$P_{copper} = I^2 R = f(T, B)$$

$$P_{iron} = f(\omega, B)$$

This means that the iron loss in the inner rotor is low. (The rotation speed ω in the formula is low.) Torque for driving the vehicle is transmitted from the inner rotor to the outer rotor. Due to the high magnetic field density in the inner air gap (high magnetic flux density B in the formula), it is easy to generate torque to drive the wheels between the outer and inner rotors. This can be done at relatively low currents (three-phase winding of the inner rotor), resulting in low copper loss in the inner rotor. The field frequency of the stator is high, but the field strength is extremely low, meaning that the iron loss of the stator is also low. No drive torque is supplied to the outer rotor from the stator. For this reason, there is no copper loss in the stator. In this mode, loss is extremely low when the vehicle is traveling at a constant speed.

When the vehicle needs to be accelerated (when the vehicle speed is high or low), a (relatively small) current can be applied through the DC winding wire of the outer rotor to create a high-density magnetic field in the outer air gap. In such cases, high torque from the stator can act on the outer rotor. The speed also causes the electric field intensity of the stator to increases, temporarily increasing the iron loss. Because significant transient acceleration usually occurs while the vehicle is in motion, these short-time energy losses are not noticeable over the entire time that the vehicle is driven. The principle described above is the underlying reason why this concept is a highly-efficient CVT.

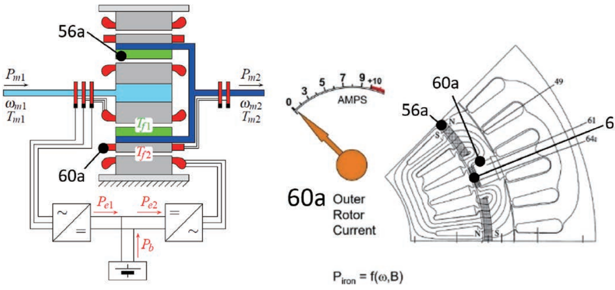

Fig. 7 Cross section of EVT and Magnetic Field Lines (DC Winding Current of 0 A)

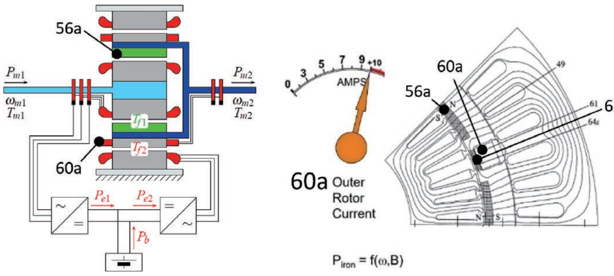

Fig. 8 Cross section of EVT and Magnetic Field Lines (DC Winding Current of 10 A)

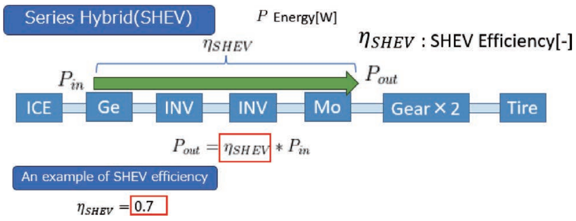

Fig. 9 Path of Power Input from Crankshaft to Series Hybrid (SHEV) System

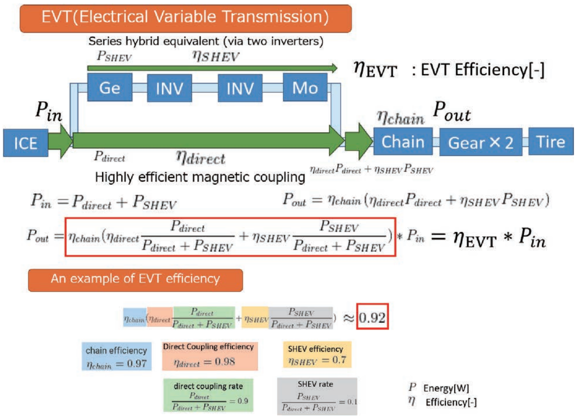

Fig. 10 Path of Power Input from Crankshaft to EVT System

The power path in the series hybrid (SHEV) is shown in Figure 9. The SHEV drives tires via an ICE, a generator, a generator inverter, a drive motor inverter, a drive motor, and gears. If the efficiency in this process is η_{SHEV}, then P_{out} (output energy) is equal to η_{SEHV} multiplied by Pin (input energy).

The power path of the EVT is shown in Figure 10. The power input to the EVT from the EVT crankshaft is transmitted to the output shaft through two paths. One is the direct path that rotates the outer rotor through the magnetic flux generated from the inner rotor. The other is the electrical path, which is transmitted to the stator through the inverter and rotates the outer rotor with the electromagnetic force generated from the stator winding. The latter is less efficient due to the intermediary power conversion. In theory, the closer the input rotational speed and the output rotational speed are, the more dominant the direct power flow through the first path becomes, increasing efficiency. Accordingly, the setting of the point where the input and output rotation speeds synchronize is an extremely important consideration.

In the EVT, the input energy, P_{in}, from the ICE is split into a direct path, P_{direct}, and a path via the SHEV, P_{SHEV}. If the respective efficiencies are η_{direct} and η_{SHEV}, then the energy after merging is obtained by adding η_{direct} multiplied by *Pdirect* to η_{SHEV} multiplied by P_{SHEV}.

In this report, the authors adopted the mechanical structure shown in Figure 16, so when the result is multiplied by the chain efficiency, the output energy, P_{out}, is obtained as shown in the formula in Figure 10.

Arranging these two formulas results in the formula at the bottom of Figure 10, where the red frame indicates the respective efficiencies.

For example, as shown in Figure 29, when the vehicle is running at a speed of 70 km/h, the efficiency of the SHEV is about 0.7.

With regards to EVT efficiency, if a chain efficiency of 0.97, direct coupling efficiency of 0.98, direct coupling rate of 0.9, SHEV efficiency of 0.7 and SHEV rate of 0.1 are used as general values, the EVT efficiency will be about 0.92.

This is why the EVT is so efficient.

In the vehicle that is the subject of this research, the extremely high transmission efficiency in a wide range of driving regions that characterizes the EVT system was achieved through comprehensive consideration of the electrical and mechanical design, and optimizing the design in consideration of the vehicle drive system as a whole.

5 INTRODUCTION OF EVT MACHINE FOR TWO-WHEELED VEHICLES

An external view of the EVT machine is shown in Figure 11.

In order to achieve the side-mounted EVT layout for the two-wheeled vehicle EVT powertrain shown in Chapter 6, the EVT machine was given an extremely thin, disc-like design. In addition, because the EVT comprises a two-rotor structure, a cantilever bearing structure was adopted for the outer rotor. In order to supply power to the DC winding section of the outer rotor and the three-phase winding section of the inner rotor, a new technology whereby a slip ring is placed inside the inner rotor was developed. For the bearing structure, a new single-sided bearing structure that ensures durability against engine vibration was designed.

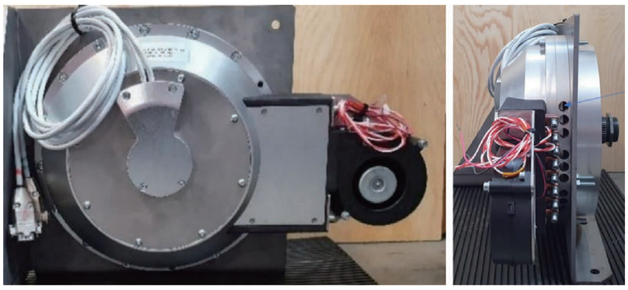

Fig. 11 EVT Machine (An angle sensor is visible in the center of the cylinder side, but this may be eliminated to achieve a sensorless design.)

Components associated with the EVT system, such as the inverter and battery system, were specially designed. Air cooling was used to cool the EVT machine, and a dynamic thermal model was created in advance to establish specifications appropriate for the vehicle in terms of aspects such as thermal design. Specifically, a heat management system that can fully withstand the challenging thermal conditions of uphill driving with two riders was achieved. Electromagnetic field analysis using the finite element method was also carried out in order to realize the performance of the EVT machine.

This section presents the results of single unit performance tests using the EVT.

Based on the references used for this paper, in an EVT system, varying the DC winding (field coil) current depending on the vehicle's driving state can be used to achieve points of high-efficiency operation. The variable characteristics of each rotor constant depending on the winding (field coil) current are shown below.

The counter electromotive force characteristics of the inner rotor in the prototype are shown in Figure 12.

The horizontal axis indicates the DC winding (field coil) current, and the vertical axis indicates the counter electromotive force of the inner rotor.

This shows that the counter electromotive force is being varied and controlled by the field coil current from the DC winding (field coil).

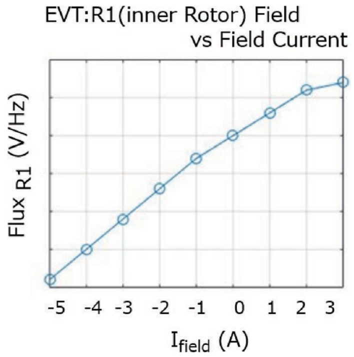

Fig. 12 Counter Electromotive Force Characteristics of Inner Rotor

The counter electromotive force characteristics of the stator are shown in Figure 13.

The horizontal axis indicates the DC winding (field coil) current, and the vertical axis indicates the counter electromotive force of the stator.

The counter electromotive force is being controlled by the field coil current from the DC winding (field coil).

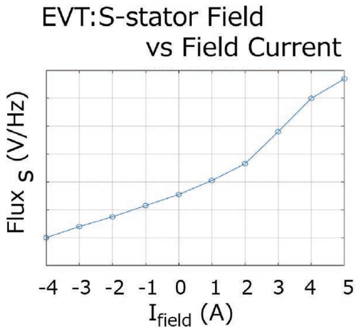

Fig. 13 Counter Electromotive Force Characteristics of Stator

The TPA (torque constant: torque per ampere) of the outer air gap is shown in Figure 14.

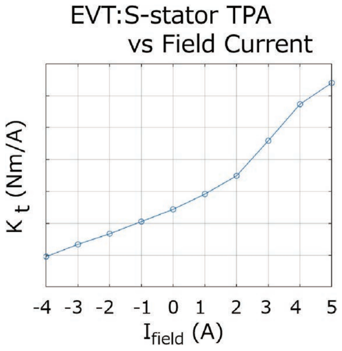

Fig. 14 Torque Constant Characteristics of Stator

For the main electrical components, based on the results of an on-desk configuration study, the authors designed and defined specifications that would maximize energy conversion efficiency in advance, then determined the motor drive method and switching elements that would maximize efficiency and carried out prototyping. In the EVT system, because driving force is transmitted from the inner rotor to the outer rotor through a magnetic path, the load on the inverter is reduced to approximately 2/3 that of series hybrids (2MOC). This is another respect in which the EVT can be considered a more efficient system than series hybrids. As a result, because the heat generation of the inverter is also reduced, the inverter can be made more compact.

6 CONFIGURATION OF EVT POWERTRAIN FOR TWO-WHEELED VEHICLES

The authors created several feasibility study examples of ICE, EVT, reducer, and power transmission layout (chain, etc.) configurations that can be mounted on a two-wheeled vehicle.

Simple diagrams of EVTs that can be fitted to a two-wheeled vehicle are shown in Figure 15. A, B and C are layouts in which the ICE and EVT are connected directly. This side-mounted EVT layout has the advantage of locating the EVT on the crankshaft, enabling the reduction between the ICE and the EVT to be omitted. Not only does this reduce costs, it also eliminates the mechanical loss associated with this reduction.

In types A and B, the drive chain is positioned on the left side of the vehicle. The difference between A and B is the final reducer.

Layout C features a reduction (chain line) on the outer periphery of the section connecting to the ICE and EVT. This has the advantage of achieving the most compact width among A, B and C, typical layouts with high transmission efficiency.

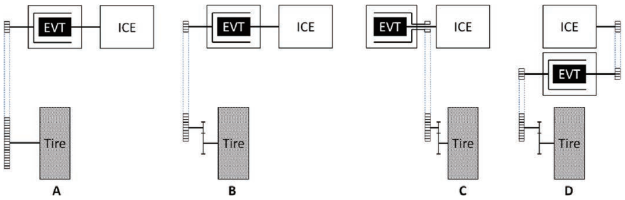

Fig. 15 Two-wheeled Vehicle-mountable EVT Layouts

In addition, the specifications of C can be adapted to conventional scooters with minimal design changes to the structure of the engine section and the reducer around the rear tire. In summary, C provides a layout that is both highly efficient and compact while also enabling easy mounting of an EVT onto an existing scooter with a proven track record in the market.

D shows a back-mount type layout in which the EVT is placed behind the ICE. This has the advantages of being narrower than A, B, and C, and making it easy to maintain the left-right balance. However, D also has disadvantages compared to the other layouts. The addition of a reducer and power transmission elements between the ICE and EVT mean that total transmission efficiency is slightly reduced and the number of peripheral parts increases. Nevertheless, the fact that D has the narrowest layout provides significant ergonomic benefits when it is used in two-wheeled vehicles, and it can therefore be considered suitable for use in two-wheeled vehicle design despite its disadvantages.

Based on the results of the above feasibility assessment, the authors decided to adopt layout C for the 125 cc scooter when installing the EVT system.

7 EVT POWERTRAIN FOR TWO-WHEELED VEHICLES

In this hybrid electric two-wheeled vehicle, a configuration whereby the inner rotor of the EVT machine is connected on the same axis as the engine was adopted. In addition, the outer rotor was connected by a chain through the gear train and is configured to transmit power to the rear wheel. Instead of a large battery, this system featured energy replenishment through the charging functions of a high-efficiency generator using a high-response gasoline internal combustion engine for two-wheeled vehicles. The EVT powertrain unit was designed with ease of assembly in mind, and the EVT machine and drive unit could be easily bolted together without changing the design of the mass-produced air-cooled 125 cc scooter engine or mass-produced frame.

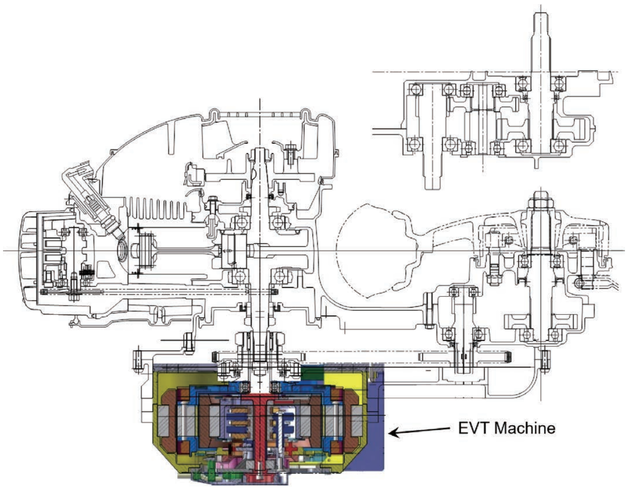

Fig. 16 Cross Section of Two-wheeled Vehicle EVT Powertrain Unit

A cross section of the powertrain is shown in Figure 16. In hybrid systems other than EVT systems, the generator and drive motor comprise separate motor components. With the EVT machine, however, integrating components through the two-rotor structure made it possible to concentrate the weight balance of the two-wheeled vehicle around the engine. The result was a vehicle with a weight balance that did not differ significantly from that of a conventional vehicle.

After considering the aforementioned hybrid function in the EVT system, the rate of regenerative braking, the rate of regenerative charging, the battery discharge rate, the depth of discharge, the number of engine starts, and tolerances, the authors' design calculations found the minimum lithium-ion battery capacity to be approximately 0.1 kWh. This is a low capacity compared to non-EVT hybrid systems. This being the case, one helmet can be stored under the seat, and mounting space comparable to that of a conventional scooter can be secured. A numerical feasibility study by the authors found that, in principle, EVT systems can operate without any lithium-ion battery capacity. (Condenser only.) This is because the EVT can generate its own power and operate the clutch using only energy from its own power generation. In such cases, it has been found to operate as a highly-efficient transmission that does not use expensive, heavy and bulky lithium-ion batteries. In this way, unlike other hybrid systems, the EVT can minimize the space required for batteries. In the course of this research and development, the lithium-ion battery capacity was set at 0.5 kWh for the purposes of investigating appeal and new experiences as a two-wheeled vehicle and in consideration of battery availability.

Figure 17 shows the prototype battery system used in the prototype vehicle. In this system, the energy input/output power and its rate and frequency in the hybrid was calculated in advance, and batteries of different capacities and types were designed and prototyped. In the prototype, lithium titanate was used for the negative electrodes to ensure long life, high input/output, and stability.

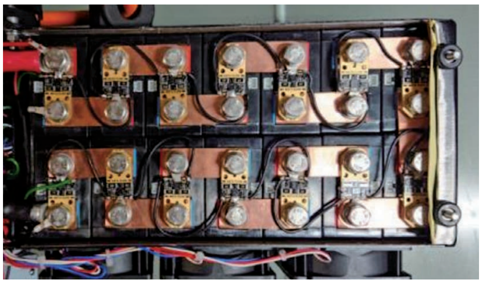

Fig. 17 Example of Prototype Battery
(Voltage: 48 V, Capacity: 0.5 kWh)

The reduction ratio specifications the EVT-equipped two-wheeled vehicle were designed to improve fuel efficiency in consideration of the characteristics of the EVT machine. Specifically, in consideration of market surveys of scooter usage, the two-wheeled vehicle's reduction ratio specifications were designed such that the inner and outer rotors of the EVT have synchronous rotation speeds in the low-speed driving range frequently used in urban areas (20-40 km/h) and in the high-speed driving range used in suburban areas (70-90 km/h). The best fuel efficiency can be achieved by increasing the frequency direct magnetic coupling between the engine and the rear wheel. Consideration was given not only to improving fuel efficiency when driving in WMTC mode, but also to improving practical fuel efficiency for users.

8 EVT POWERTRAIN CONTROL STRATEGY

In the two-wheeled hybrid electric vehicle fitted with an EVT system, in order to enable application to a wide range of hybrid systems, power generation control technology, driving control, and energy management control were constructed into extremely simple and versatile mechanisms. A data flow diagram (DFD) of the hybrid system is shown in Figure 18.

The structural layout and basic operating mechanisms of the EVT vehicle system are shown in the component diagram in Figure 19.

A vehicle control unit (VCU) has the role of controlling the vehicle (driving control, energy control, arbitration control and fail safe control). A motor control unit (MCU) has the role of controlling drive torque. A generator control unit (GCU) has the role of controlling the amount of power generation. A battery management system (BMS) monitors the state of the battery.

In the operation of this system, the VCU receives the rider's accelerator position and power information from the MCU, GCU, and BMS.

First, the power generation control technology features a high-efficiency power generation control strategy that significantly improves fuel efficiency through significant changes to the engine operating point range compared to that of conventional two-wheeled vehicles during power generation. The core means to achieve a highly-efficient hybrid system is to perform power generation control as efficiently as possible relative to the electric power required for driving.

Through accurate control of the rotation speed of the directly-connected inner rotor relative to the engine torque controlled by the electronic throttle valve, it is possible to follow the optimal fuel consumption line and achieve highly-efficient power generation control.

The input/output performance of lithium-ion batteries, engine generators, and drive motor components changes depending on temperature, including when operating in high-temperature and low-temperature environments. This is an important factor with regards to the requirements for a hybrid system containing lithium-ion batteries.

This time, the authors constructed a robust system that can obtain optimum output across a wide temperature range by performing arbitration control (Figure 18) based on state of function (SOF) information regarding the temperature of each component.

In addition, by implementing control that maintains drive output by obtaining output from the engine, the authors have built a system that guarantees performance even when the output that can be taken from the battery is reduced at high or low temperatures.

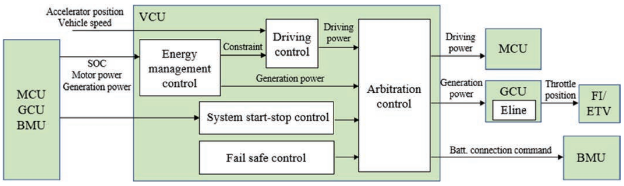

Fig. 18 Data Flow Diagram (DFD) of Hybrid System

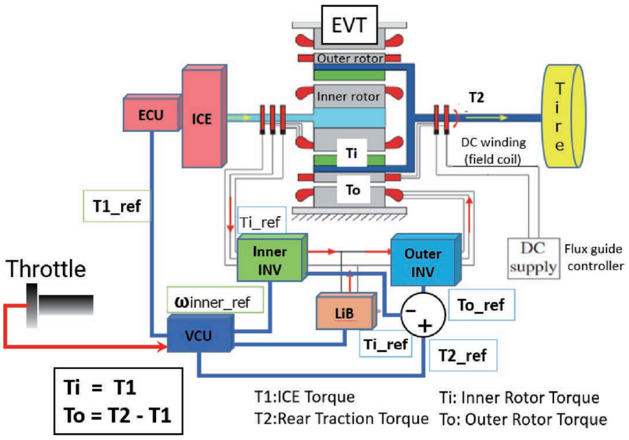

Fig. 19 EVT Vehicle System Component Layout

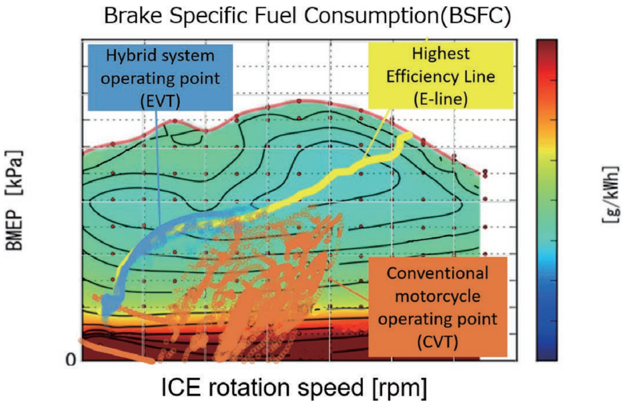

Fig. 20 Brake Specific Fuel Consumption (BSFC) MAP and Highest Efficiency Line Tracking Control

Figure 20 shows the relationship between the fuel consumption rate and engine output. The yellow line indicates the operating points at which fuel consumption is minimized relative to the required engine output. Comparing the history of operating points during WMTC mode driving between existing two-wheeled vehicles (red) and the EVT system (blue), it can be seen that the EVT system follows the highest efficiency line and generates electricity with high efficiency. In conventional two-wheeled vehicles and some hybrid systems, there were cases where it was not possible to perform control to track the highest efficiency line because factors such as mechanical constraints relative to the vehicle speed and required driving force restricted the engine rotation speed. The line of operation is particularly inefficient for ICEs at low rotation speeds.

In the EVT system, the two-rotor structure means there are no similar mechanical constraints, making it possible to follow the highest efficiency line.

In terms of the engine sound design, which is a desirable characteristic particular to users of two-wheeled vehicles, control that increases the engine speed as obediently as possible to the power requested by the rider was implemented with the aim of achieving a natural audible sensation and pulsing sensation without discomfort across low- to high-speed regions. The image of a sports motorcycle was a particularly prominent influence.

When the vehicle is running at low speeds, power generation by the engine is stopped, which improved driving efficiency at low speeds by enabling EV-only driving with power supplied from the battery.

In terms of driving control, the rear tire was controlled to provide a natural-feeling riding that responds to the rider's intentions.

With conventional scooters, there is a long response time between the rider opening the throttle and the vehicle gaining acceleration. Users who prefer sporty driving tend to feel that this response in conventional vehicles is poor.

The EV system is a strong hybrid. It is fitted with a large motor that achieves the sharp acceleration unique to electric vehicles in a wide range of speed regions. Due to the two-rotor structure of the EVT, the motor on the outer rotor side has a large outer diameter and can increase the output. In other words, the EVT can achieve more powerful drive torque than non-EVT hybrids.

The regeneration function was used to provide the rider with a new experience. The one-throttle operation function enables the rider to adjust their speed by operating the throttle only, without using the brake lever. This provides enjoyable riding and a new feeling not found with conventional scooters.

Finally, in terms of energy management control, appropriate integrated control of energy flow arbitration is applied to optimize energy distribution in response to the power requested by the rider, in consideration of the operating state of the engine, EVT machine, and battery.

Three basic energy management control modes were set for operating the EVT system, and a strategy of performing energy management control according to the operating state of the powertrain was adopted. A basic example of the area logic for EV driving modes and HEV driving modes is shown in Figure 21. P^* in the diagram indicates the required value for generator generated power. No. I indicates the EV driving mode, and No. II indicates the HEV driving mode. The required power generation depending on the remaining battery was defined.

This formula has been included in the diagram for reference purposes.

No. III is configured to stop charging when the lithium-ion battery becomes fully charged in situations such as long downhill sections and discharge regenerative power using the engine as a load.

This made it possible to achieve highly-efficient, optimized energy management and arbitration, even when freely generating driving force in real time according to the driving conditions of the two-wheeled vehicle. The modes are described below.

【I. EV driving mode】
Requirement: Drive is provided using battery power only.
①The two-wheeled vehicle is fully electric.
②During deceleration, regenerative deceleration energy is recovered with the lithium-ion battery.
Reason: Fuel efficiency is improved by refraining from running the generator and engine when there is leeway in the SOC.

【II. HEV driving mode】
Requirement: When the SOC is low, the power generated exceeds the traction motor's required

output [W], and when the SOC is high, the power generated is less than the motor's required output [W].

①The engine power is driven via a magnetic coupling. Drive is provided using electricity generated by the engine.

②Drive is provided by the power generated by the engine, and the surplus is charged to the lithium battery.

③Used as a boost mode, using both power generated by the engine and power from the lithium battery to accelerate.

Reason: To stabilize the SOC and reduce battery deterioration and to enable control with a low-capacity battery.

【III. SHEV (energy consumption) mode】

Requirement: Charges the battery with regenerative power. If the battery cannot be charged, power is consumed by running the engine as a load. (Activated with battery overcharge prevention.)

Reason: To prevent battery deterioration and overcharging while avoiding reducing vehicle braking force as much as possible

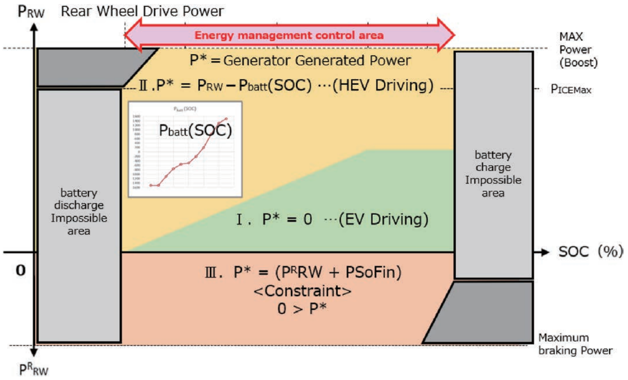

Fig. 21 Basic Example of Hybrid Driving
(Energy Management Block)

9 EVT POWERTRAIN DEVELOPMENT ENVIRONMENT

This section describes the environment and processes in which EVT system development took place.

In the course of this research and development, the powertrain (the engine, battery, and electric drive unit) is more complex than a conventional engine system. For this reason, in moving forward with the project, research and development was carried out in a time-efficient manner, using digital technology to determine performance trends during the initial stages without manufacturing physical equipment.

In the case of four-wheeled vehicles, SILS, HILS, and Virtual Reality Bench (VRS bench) are known methods used for verification. With two-wheeled vehicles, however, the power train itself is extremely small, and motion systems must have low inertia and high responsiveness. In the past, it had been difficult to apply VRS bench, which is a simulator based on four-wheel vehicles, to the development of hybrid electric two-wheeled vehicles.

As a result, the authors carried out independent development of a dedicated VRS bench system exclusively for hybrid electric two-wheeled vehicles in parallel with their research and development on the EVT powertrain system. This VRS bench, comprises the actual components of the powertrain for the hybrid electric two-wheeled vehicle subject to evaluation and a low-inertia motor with a uniquely designed low-inertia, high-response dynamo function.

Specifically, the authors designed a 10kW high-performance IPM motor system that matches the prototype hybrid system as a bench measurement system.

By coordinating the VRS control and the prototype hybrid control within the same control unit, control safety relative to normal four-wheel or two-wheel VRS benches was ensured.

In addition, unifying the system enabled the realization of an accurate, low-delay energy measurement environment.

The authors constructed a new bench measurement system that can realize appropriate failure processing even in limit tests of prototype hybrid systems.

This vehicle simulator can reproduce specific vehicle driving conditions that based on assumed vehicle behavior by applying a model that virtually reproduces the dynamics of the vehicle.

Through this, it was possible to achieve modeling and system identification regarding the dynamic characteristics the powertrain fitted with a SHEV and an EVT system and implement a theoretical approach to control and compatibility design through front loading.

This made it possible to perform verification relating to evaluation and compatibility processes, which were previously performed on finished vehicles, from the initial stages, including steady and transient states. This succeeded in significantly shortening the evaluation test period and improving efficiency in the development of the hybrid electric two-wheeled vehicle.

Images of the exterior of the dedicated VRS bench system for hybrid electric two-wheeled vehicles is shown in Figure 22 for reference.

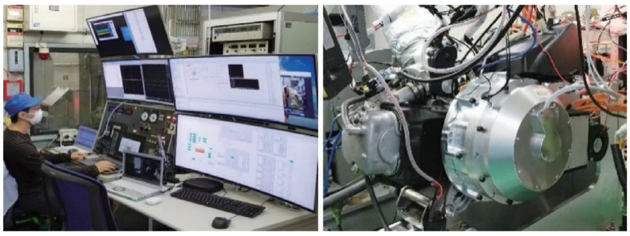

Fig. 22 EVT VRS Bench System

This VRS bench was used to identify the mechanism by which mechanism net mean effective pressure (NMEP) is consumed during driving.

This is essential in order to investigate ways to improve the mode fuel efficiency as presented in this report.

For reference, Figure 23 shows NMEP distribution destinations in series hybrids (SHEV) studied using simulation.

In the WMTC mode driving speed range, friction mean effective pressure (FMEP) and running load resistance are the dominant NMEP distribution destinations, and electronic transmission loss is about 20-25%.

Although no detailed explanation is given in this report, similar studies and verifications were also conducted for existing CVT transmissions and EVT transmissions. In the electronic transmissions, in addition to improved mechanical transmission efficiency, the control strategy for the hybrid system was created after comprehensive organization of fuel efficiency improvement, including control using regeneration.

In addition, the accuracy of the results shown in the comparison of Target and Measurement in Chapter 10 was ensured by feeding the data obtained on the VRS bench back to the desktop simulation and performing analysis that included the chassis test results.

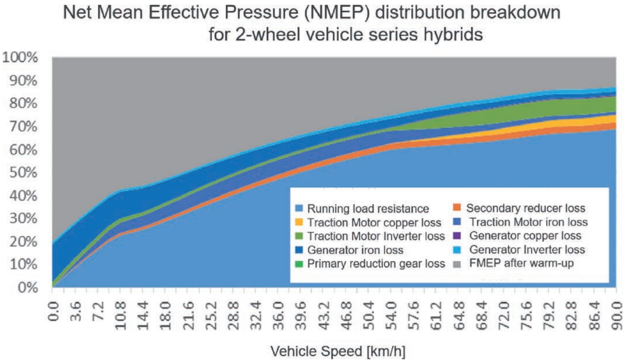

Fig. 23 Net Mean Effective Pressure (NMEP) Distribution Destinations in Series Hybrids (SHEV)

10 HYBRID ELECTRIC TWO-WHEELED VEHICLE PERFORMANCE AND FUEL CONSUMPTION MEASUREMENT RESULTS

This section describes the results of fuel consumption and performance measurement on the prototype hybrid electric scooter created in the course of this research and development.

Figure 24 shows a comparison of vehicle weight, fuel consumption measurement results, and acceleration time for the series hybrid-equipped vehicle constructed for this research and development and the EVT-equipped vehicle.

The prototype vehicle is fitted with the components required to construct a hybrid system without changing the main engine components or vehicle frame of the existing scooter. In this case, changing the 125 cc scooter to a hybrid system increases vehicle weight by a maximum of approximately 30 kg.

In this study, measurement of fuel consumption in WMTC mode was the first priority when carrying out research and development. For this reason, the acceleration performance target was the same as the BASE vehicle. This is the reason why the 0 to 20 m acceleration times shown in Figure 24 are more or less in equilibrium across all three vehicle types. However, relative to ICE vehicles, the two types of hybrid electric two-wheeled vehicle can generate torque from low vehicle speeds through electrical responses and do not require time to engage the clutch. It is therefore conceivable that acceleration time can be easily improved by rewriting driving control compared to CVT vehicles with engines.

As a result, it can be seen that EVT vehicles offer improvements in acceleration time compared to other vehicles.

The authors intend to continue investigating acceleration performance and to report on this in a subsequent paper.

	Vehicle weight (kg)	Transmission type	Motor Type	Measurement	
				Fuel comsumption [km/L]	Acceleration time (0-20m) [sec]
EVT (2M splitter)	125	Electric	Dual Rotor (8P48S) (distributed winding)	WMTC mode full regeneration 84.9 (Target 85.2)	2.63
Series Hybrid (2M0C)	128		IPM (8P12S) 2 pieces used (concentrated winding)	WMTC mode full regeneration 81.1 Regeneration equivalent to ICE Brake 74.3	(2.77)
BASE	99	Mechanical	N/A	62.2	2.77

Fig. 24 Comparison of Vehicle Weight, Fuel Consumption Measurement Results and Acceleration Time

Fig. 25 Exterior View of Vehicle Fitted with EVT System

Fig. 26 Exterior View of Vehicle Fitted with Series Hybrid

In this research and development, WMTC mode running tests were conducted to confirm the fuel consumption rate of the two types of hybrid vehicle (Figure 25 and Figure 26) for which effectiveness had been confirmed.

Figure 27 shows the WMTC mode driving pattern for this test.

The upper section of Figure 27 shows the WMTC mode vehicle speed.

The lower section of Figure 27 is an enlarged view of the 0 to 600 second portion during WMTC mode driving, showing the operation results of the hybrid control strategy.

The upper half of the lower diagram in Figure 27 shows the vehicle drive control. In terms of vehicle drive control, the EVT components adopt a control strategy that regenerates power in accordance with the rider's target driving speed. In addition, in this research and development, drive control was set up to recover as much regenerative energy as possible.

The lower half of the diagram in Figure 27 shows the energy management control strategy by indicating pure electric driving and hybrid driving.

A control strategy that uses electric driving in the low-speed range where the load is light, and transitions to hybrid driving in the high-load range was adopted.

From the above results, it can be seen that hybrid operation strategy was properly realized through automatic control. Specifications equivalent to existing mass-produced models were applied for the engine control used in this research.

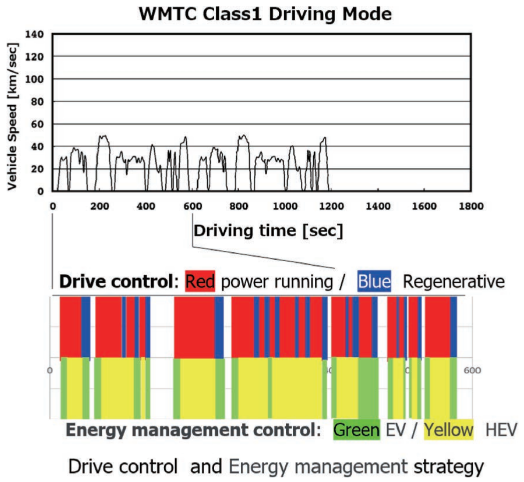

Fig. 27 Top Diagram: WMTC (Worldwide-harmonized Motorcycle Test Cycle Mode) part1 Reduced Bottom Diagram: Hybrid Driving Strategy (Drive Control and Energy Management)

Next, Figure 28 shows the WMTC mode driving fuel efficiency results.

Weak series hybrid system regeneration is a configuration that performs regeneration equivalent to the engine brake of the base CVT vehicle, and strong regeneration is a configuration that recovers as much regenerative energy as possible throughout the WMTC mode.

The EVT uses a configuration that recovers as much regenerative energy as much as possible throughout the WMTC mode.

In research and development relating to the EVT, the target fuel efficiency was 85.2 km/L in WMTC mode, a 37% improvement in fuel efficiency compared to the base vehicle. As shown in Figure 28, it was confirmed that the actual prototype vehicle achieved mode fuel consumption of 84.9 km/L. This means that, not only did the EVT powertrain system of the prototype vehicle improve fuel efficiency by approximately 37% compared to the base vehicle, this highly-efficient system was shown to surpass the series hybrid system that was researched and developed at the same time.

The transmission efficiency relative to speed for the two hybrid systems is shown in Figure 29.

The transmission efficiency was calculated using the η_{SHEV} parameter shown in Figure 9 and the η_{EVT} parameter shown in Figure10.

Based on the measurement results, it was found that the EVT system had higher efficiency than the series hybrid across all regions.

The EVT's inner and outer rotors are designed to have synchronous rotation speeds in the low-speed driving range (20-40km/h), which is frequently used in urban areas, and in the high-speed driving range (70-90km/h), which is frequently used in suburban areas. As a result, it was confirmed that the EVT efficiency is high.

Furthermore, in the low-speed driving range, where the relative contribution of mechanical loss is large, the maximum efficiency was at 40 km/h, and the EVT was found to have higher efficiency than the SHEV. (Figure. 29)

As mentioned in Chapter 9, series hybrid system losses are 20-25% relative to NMEP.

Since the EVT transmission efficiency is about 15% higher than that of the series hybrid system, the EVT system improves fuel consumption by about 5% compared to that of the series hybrid system.

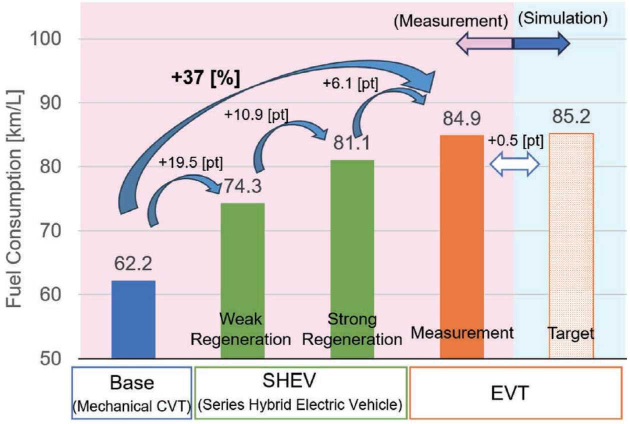

Fig. 28 Fuel Consumption Comparison
(Base Vehicle, Series Hybrid (SHEV) and EVT)

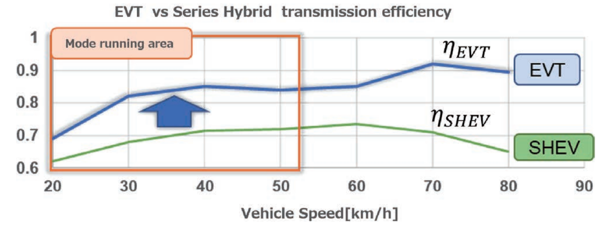

Fig. 29 Transmission System Efficiency Comparison
(Series Hybrid (SHEV) and Electrical Variable Transmission (EVT)) (Measured with VRS Bench System)

At this stage, further improvements to efficiency merit consideration.

In this test, a control method whereby the EVT's inner rotor tracks the ICE's highest efficiency line was used for the power generation function. Based on this, it may be possible to further improve fuel efficiency by optimizing the power generation function on both the ICE's highest efficiency line and the EVT's efficiency map.

In addition, the efficiency of the EVT powertrain system can be further improved by bringing the two rotors closer to synchronous rotation when in WMTC mode (see Figure 20 and Figure 30). As shown in Figure 30, preliminary test results indicate that optimizing the EVT powertrain system setup in this way can improve system efficiency at 30 to 60 km/h by approximately 5 to 10%. Based on these results, WMTC mode driving fuel consumption of 91.2 km/L (a 47% improvement in fuel consumption compared to the base vehicle (see Figure 31)) would be expected, meaning and further improvements in fuel consumption can be achieved.

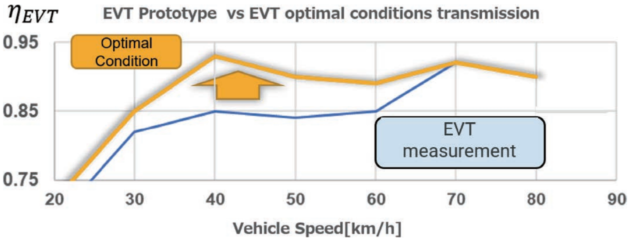

Fig. 30 Transmission Efficiency Improvement when ICE and EVT Efficiency Characteristics are Considered
(Measured with VRS Bench System)

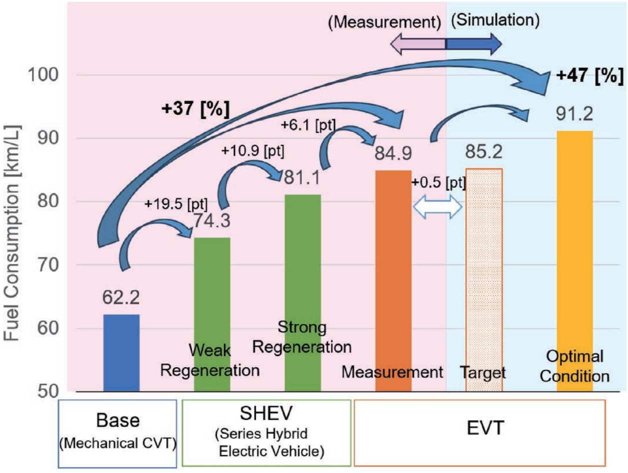

Fig. 31 Fuel Consumption Comparison
(Base Vehicle, Series Hybrid (SHEV) and EVT)

In the course of this research and development, mass-produced engines were used, no improvements were made to mechanical components, and fuel consumption studies were carried out using conventional mass-produced air-cooled single-cylinder ICEs. However, improvement in the efficiency of the engine itself is also a highly significant factor, and it goes without saying that applying fuel efficiency improvements to the engine used in this research can lead to even greater improvements in fuel efficiency.

Although not described in this report, changing from an air-cooled engine to a water-cooled engine is widely known to improve fuel efficiency. If the ICE were to be water-cooled, it may be possible to achieve fuel consumption of 100 km/L or more. In summary, the use of hybrid electric two-wheeled vehicles can make it possible to satisfy the conflicting requirements of environmental performance in terms of fuel efficiency and elements that make two-wheeled vehicles enjoyable to ride, such as acceleration performance. Hybrid electric two-wheeled vehicles make it possible to achieve improved environmental performance, new sensations and enjoyable riding particular to electric vehicles, and long-distance cruising with large energy storage particular to ICEs. Reporting on exhaust gas is not carried out in this report. Hybrid systems have the advantage of enabling ideal driving conditions to be maintained by using a large motor in the engine to change the operating point. At the same time, adaptation including engine control elements such as engine and catalyst warming control, change of mind and evaporative control is needed, meaning that thorough examination is required.

The authors intend to report on this in a subsequent paper.

11 POSSIBILITIES FOR HYBRID ELECTRIC TWO-WHEELED VEHICLES

This two-rotor technology is compact because the generator and drive motors are integrated, making it effective for use in two-wheeled vehicles with strict component mounting requirements.

However, with regards to increased mass due to hybridization, it will be necessary to carry out sufficient preliminary verification of the front-rear and left-right balance, which are design conditions particular to two-wheeled vehicles, and the impact of additional mass on vehicle behavior.

This section describes an example of study based on the aforementioned approach. Specifically, it is possible to expand application of the EVT machine from the small scooter category to the motorcycle category while maintaining the same outer diameter. This is achieved by changing the overall length of the EVT machine. According to on desk calculations by the authors, the EVT machine mechanical shaft output can be improved from 10 kW to 30 kW equivalent by changing the EVT machine voltage from 48 V to 96 V.

At present, while the availability of space to store the lithium-ion battery, which is an important component separate from the EVT machine, remains to be confirmed before a maximum output of 30 kW can be achieved, the authors consider this to be a possibility. In this regard, a lithium-ion battery that can be laid out three-dimensionally to fit the narrow mounting space on two-wheeled vehicles is desirable. The mounting position must also be selected after considering future improvements in lithium-ion battery performance.

In another study of specifications conducted by the authors, in which the EVT system functions were limited, preliminary studies showed that an EVT's magnetic coupling torque is sufficient for operation without using lithium-ion batteries, which are expensive, bulky, and heavy. In such cases, the fact that no lithium-ion battery is required would make the EVT system smaller and lighter. In this system that limits the functions of the EVT according to the purpose, while limitations include the difficulty of achieving electric driving and boost modes, it is known that ICE driving efficiency can be improved, and that fuel consumption and acceleration performance can be improved compared to conventional vehicles by combining idling stop and regeneration functions.

Below are examples of a hybrid electric two-wheeled vehicles fitted with powertrains featuring the EVT system with an output equivalent to 30 kW envisaged by the authors earlier in this paper (see Figure 32 and Figure 33).

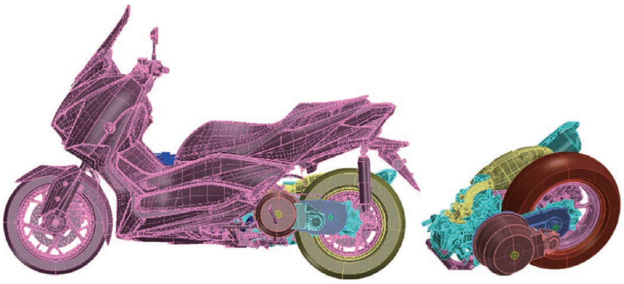

Fig. 32 Example of Side-mounted EVT (30 kW) on Large Scooter

According to the authors' configuration study, it is possible to generate a maximum output of 30 kW, which exceeds that of the conventional two-wheeled vehicle category, while reducing greenhouse gases by combining a high-output EVT system with an ICE of 15 to 20 kW.

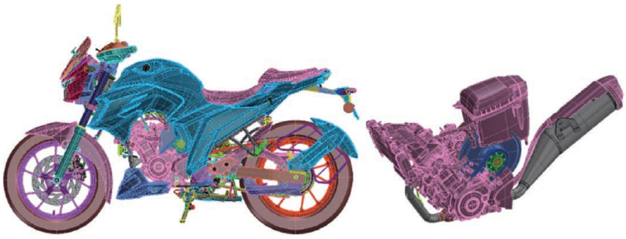

Fig. 33 Example of Rear-mounted EVT (30 kW) on Motorcycle (Example of back mounting: EVT mounted behind ICE)

As described above, based on the authors' study, EVT machines can be easily scaled to changes in the mechanical shaft output of the two-wheeled vehicle and can be expected to improve output by increasing voltages. In other words, application in a wide range of two-wheeled vehicle categories may be possible. Prototype EVTs up to 180 kW already exist for four-wheeled vehicles, and the authors believe that there are wide-ranging potential future applications.

12 CONCLUSION

The basic principle of the EVT system is based on a power transmission (F. Porsche) invented in 1909. (See Figure 34.)

In research and development on new hybrid systems, in contrast to previous two-wheeled vehicle development mainly focused on the mechanical domain, the authors took on the challenge of innovating to create value by reaffirming electrical machinery technology built 110 years ago and combining it with modern advancements. By taking on this challenge, the authors were able to put forward a hybrid electric two-wheeled vehicle that can play a part in environmental protection measures and provide value for new users.

By adopting the EVT system for two-wheeled vehicles, the authors were able to improve power performance, environmental performance, and drivability, which were considered to be mutually exclusive in conventional two-wheeled vehicles, in accordance with their respective requirements. This has shown that hybrid electric two-wheeled vehicles equipped with EVTs are highly effective.

In the two-wheeled vehicle category, the use of highly-efficient strong hybrids, as typified by hybrid electric two-wheeled vehicles with EVTs, will make it easier to comply with future laws and regulations, as has been shown in the realm of four-wheeled vehicles.

With two types of hybrid system with different mechanical structures as the subject, the authors posited and constructed a platform hybrid system control that can flexibly respond to different hybrid topologies. This makes it possible to flexibly meet diverse performance, appearance, and design requirements for two-wheeled vehicles.

Moving forward, there is an urgent need to protect the environment and build a sustainable society for future generations. Use of fossil fuels must be reduced. In recent years, there has also been a shift towards synthetic fuels, with the aim of realizing a more sustainable society. It is hoped that hybrid electric motorcycles that adopt the EVT system used in the course of this research and development will be able to provide customers with the same enjoyable riding they have experienced up to now while also significantly improving fuel efficiency.

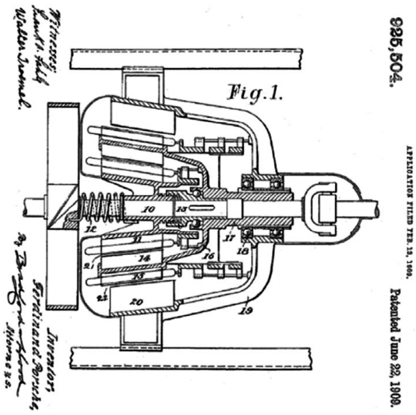

Fig. 34 Two-rotor Transmission Invented in 1909 (F. Porsche)

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■著者

古田 秀樹
Hideki Furuta
技術・研究本部
技術開発統括部
制御システム開発部

吉田 潤
Jun Yoshida
技術・研究本部
技術開発統括部
制御システム開発部