

Electric Drive Motor for Fuel Cell Vehicle FCX Clarity

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ABSTRACT

A new DC brushless motor has been developed as the electric drive motor for the Honda FCX Clarity fuel cell vehicle.

Due to the demands of vehicle packaging, a coaxial configuration was employed for the drive motor and gear box, and the power drive unit has been integrated with the drive motor, enabling the size of the overall drive unit to be reduced. The integration of the drive motor and gear box has reduced friction, contributing to increased operating efficiency.

An IPM rotor has been employed to increase motor speed in order to increase maximum vehicle speed, and to increase power output in order to enhance vehicle performance. The use of a limit value for the inductance setting that enables greater power to be achieved at maximum motor speed has reconciled high motor speed with high power.

These innovations have enabled the length of the drive unit to be reduced by 162 mm and its height to be reduced by 240 mm. The electric drive motor achieves a maximum power of 100 kW, maximum torque of 256 Nm, and maximum speed of 12 500 min⁻¹. In addition, a maximum motor drive efficiency of 97% has been achieved.

1. Introduction

Against a background of increasing global environmental awareness, further reductions in CO₂ emissions are demanded in order to reduce automotive emissions and to combat global warming. Responding to these demands, Honda moved forward with the development of the Honda FCX fuel cell vehicle (2003 model year FCX) as the ultimate environmentally-friendly automobile. In 2002, Honda led the world by leasing fuel cell vehicles to the Japanese government and the City of Los Angeles in the United States⁽¹⁾. In order to increase the diffusion of fuel cell vehicles, the company went on to develop the New Honda FCX (2005 model year FCX), which was fitted with a proprietary fuel cell stack that displayed enhanced performance at low temperatures. This was the world's first fuel cell vehicle able to be used at temperatures below freezing, and the vehicles were leased to the New York State administration in 2004 and the Hokkaido prefectural government in 2005⁽²⁾.

In July 2008, Honda commenced marketing the FCX Clarity, which has as its core Honda's proprietary V Flow FC (Vertical Gas Flow Fuel Cell) stack, a cell configuration in which hydrogen and air flow vertically⁽³⁾. The FCX Clarity has been developed not only to realize the ultimate in clean automotive performance, but to

create new value and offer new appeal as an automobile. The Clarity's short nose and long wheel base, enabled precisely by the use of fuel cells in the vehicle, give it a spacious cabin, and it offers continuous smooth and powerful acceleration from takeoff to top speed. The drive motor employed in the FCX Clarity (the MCF31) has been reduced in size and increased in efficiency, power and speed against the MCF21 motor used in the 2005 model year FCX.

This paper will discuss the technologies employed in the MCF31 and the achieved performance of the motor.

2. Development Goals

The two main goals established for the development of the MCF31 motor were the achievement of:

- (1) Increased compactness and higher efficiency in the drive unit
- (2) Increased power and speed

In order to enable the realization of the design – featuring a short nose and low overall height – that had been made possible by the use of fuel cells, the motor magnetic circuits would be reduced in size and the motor, gearbox, and power drive unit would be integrated to make the drive unit more compact.

In order to realize a 60% level of energy efficiency,

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the achievement of a maximum drive efficiency of 97%, equivalent to that of the MCF21, was established as a target for the motor, to be balanced with the power performance targets described below.

Power performance targets were established from the vehicle performance requirements as follows.

Equation (1) shows the relationship between maximum drive power ($F_{\max}$) and maximum vehicle speed ($V_{\max}$), and maximum motor torque ($T_{\max}$) and maximum motor speed ($N_{\max}$)⁽⁴⁾.

$$F_{\max} \cdot V_{\max} = 2\pi \cdot T_{\max} \cdot N_{\max} \quad (1)$$

In order to achieve the maximum speed of 100 mile/h (160 km/h) that had been established as vehicle targets and maximum drive power required during acceleration, a figure of 12 500 min⁻¹ was established for the maximum motor speed, $N_{\max}$, taking into consideration the range for the reduction ratio of the coaxial gearbox and a balance with increased friction, and the like. From this figure, a figure of at least 256 Nm was established for the maximum motor torque, $T_{\max}$.

A figure for minimum motor torque (bottom value) at 0 min⁻¹ was established from the minimum drive power required for acceleration up a slope from a stationary state. At the same time, the torque constant was increased in order to help ensure that the phase current value at 0 min⁻¹ did not exceed the maximum allowable inverter current.

The target for maximum motor power was established as 100 kW to enable the realization of an equivalent level of passing acceleration performance to a 2.4 L-class gasoline vehicle. In addition, a target for continuous power output was established from the torque conditions required for continuous operation at maximum speed and to enable the vehicle to be stopped while climbing a hill using only accelerator operation, and the achievement of reduced loss and enhanced cooling performance was planned.

In order to increase energy efficiency, the minimum input voltage to enable maximum motor power to be achieved was set as the output voltage of the fuel cell stack with no voltage booster employed. With this as the input voltage, it would be necessary to reconcile the antagonistic requirements of a high torque constant and the achievement of the necessary power at maximum motor speeds.

3. Technologies Employed

Table 1 shows the main specifications of the MCF31 motor. Figure 1 provides an overview of the external appearance of the integrated drive unit formed from the motor, gearbox, and power drive unit.

The basic motor type is a permanent magnet (PM) motor that can use reluctance torque, as employed for the MCF21. An eight-pole rotor was selected in order to control loss (in particular high-frequency core loss), noise, and vibration.

Table 1 Comparison of motor specifications

	MCF21 (2005 model year FCX)	MCF31 (FCX Clarity)
Type	PM synchronous motor	PM synchronous motor
Phase	3	3
Number of poles	12	8
Rotor type	Salient SPM	IPM
Magnet	Nd-Fe-B	Nd-Fe-B
Cooling system	Water-cooled	Water-cooled

3.1. Drive Unit Configuration

The configuration discussed below was employed to reduce the size of the drive unit in order to enable the vehicle packaging to be realized. The transmission efficiency of the drive unit was also increased in order to increase the energy efficiency of the vehicle.

3.1.1. Integration of motor and power drive unit

The total height of the drive unit was reduced by integrating the power drive unit and the motor, to enable the total vehicle height to be reduced and to help protect pedestrians in the event of a collision.

To enable integration of the motor and power drive unit, motor vibration was reduced and vibration resistance of the power drive unit was increased. This has contributed to enabling the height of the drive unit from the bottom of the motor to be reduced by 240 mm against the 2005 model year FCX, as shown in Fig. 2, resulting in reduced space needed to fit the motor.

3.1.2. Coaxial configuration of motor and gearbox

The total length of the drive unit has been reduced in order to realize the short nose design and help ensure occupant safety in a collision.

The rotor shaft of the motor is hollow, and the drive shaft passes through it, enabling the employment of a coaxial configuration for the motor and the gearbox. The

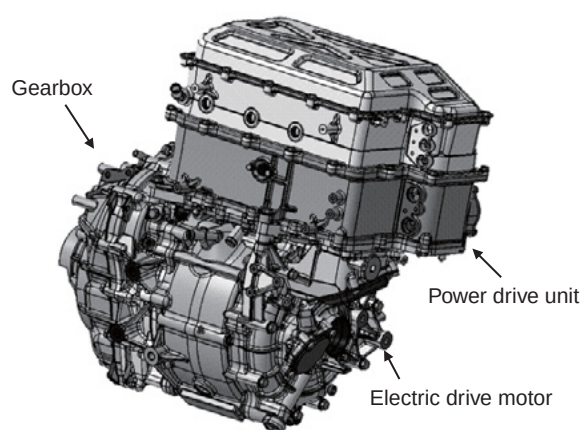


Fig. 1 Appearance of drive unit assembly

groundbreaking new configuration achieved in this motor, together with the reduction of the external diameter of the motor by 4%, has enabled the length from the center of the differential shaft to the front of the motor to be reduced by 162 mm against the 2005 model year FCX, as shown in Fig. 3. This has also reduced the space needed to fit the motor.

3.1.3. Motor oil lubrication

Friction has been reduced in the drive unit for increased transmission efficiency, in order to increase the energy efficiency of the vehicle.

In the 2005 model year FCX [Fig. 4(a)], the motor and the gearbox were housed separately, and their bearings were lubricated using grease and gear oil respectively. In the FCX Clarity [Fig. 4(b)], the oil resistance of the internal components of the motor has been increased, and the same housing has been employed for the motor and the gearbox. The number of oil seals

has been reduced, and newly developed bearings lubricated by gear oil have been employed, enabling the achievement of a maximum reduction of 36% in friction against the 2005 model year FCX (Fig. 5).

In addition, the temperature of the stator windings has been rendered uniform by the use of gear oil in the motor, enabling both power and the range of continuous operation to be increased.

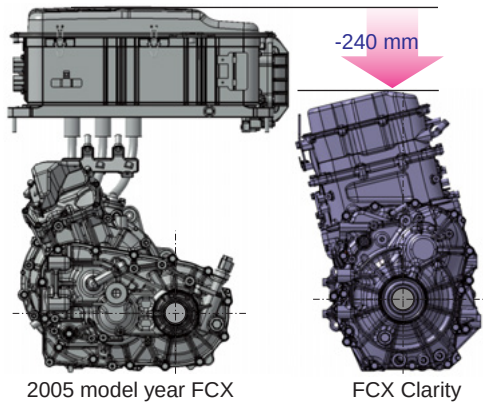


Fig. 2 Comparison of total height of drive unit

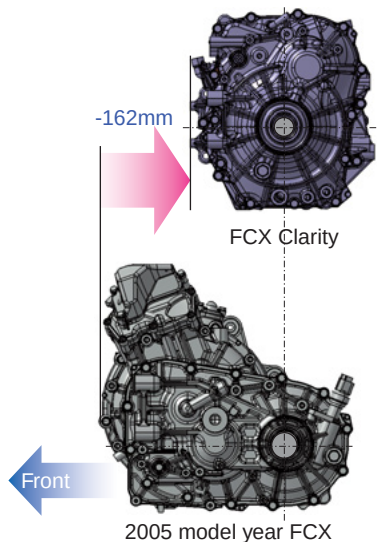


Fig. 3 Comparison of total length of drive unit

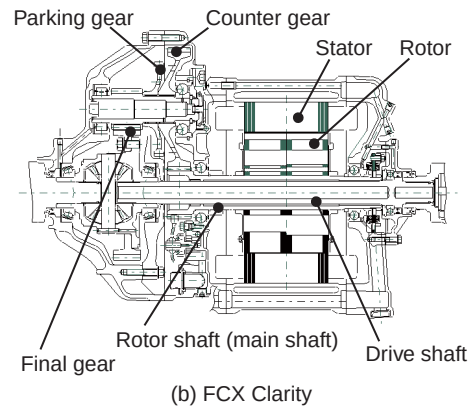
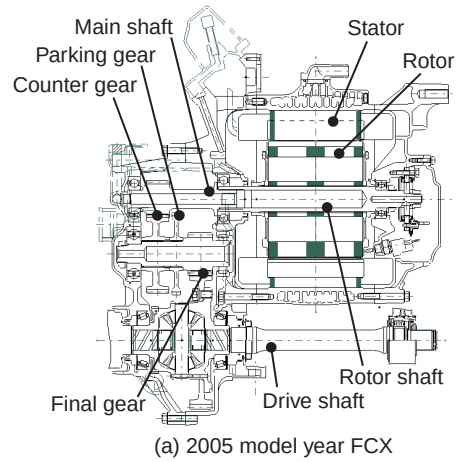


Fig. 4 Section of drive unit

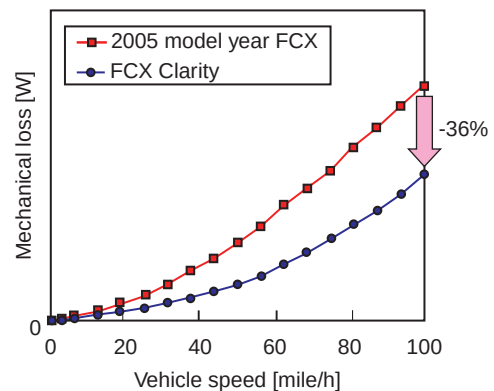


Fig. 5 Comparison of mechanical loss

3.2. PM Motor Able to Use Reluctance Torque

A PM motor that can use reluctance torque was selected as the basic motor type, as in the case of the MCF21, in order to realize high efficiency across the entire driving range.

As Fig. 6 shows, in a PM motor that can use reluctance torque, the magnetic torque generated by the rotor magnets and the reluctance torque generated by the salient poles of the electrical steel sheets between the magnets can be combined, enabling the degree of use of the magnets to be reduced.

The torque generated by a motor that can use reluctance torque, T_q , is expressed by Eq. (2). With the torque axis expressed as the q -axis and the flux field axis expressed as the d -axis, ϕa is the magnetic flux linkage of the magnet, Pn is the number of pole pairs, i_d and i_q are the currents at the d - and the q -axes respectively, and L_d and L_q are the inductances at the d - and q -axes respectively. The first term on the right-hand side of the equation expresses magnetic torque, and the second term expresses reluctance torque⁽⁵⁾.

$$T_q = Pn \cdot \phi a \cdot i_q + Pn(L_d - L_q)i_d \cdot i_q \quad (2)$$

From the second term, it is clear that reluctance torque is proportional to $(L_d - L_q)$.

The current required for field-weakening drive, i_d , is expressed by Eq. (3), where ω is the speed of the electrical angle and V_b is the input voltage.

$$i_d = -\frac{\phi a}{L_d} + \frac{1}{L_d} \sqrt{\frac{V_b^2}{\omega^2} - (L_q \cdot i_q)^2} \quad (3)$$

Achieving a high inductance, which increases L_d , would have the effect of reducing the current required for field-weakening drive.

However, the power, P , can be approximated by Eq. (4), showing that increasing inductance reduces the maximum power at the voltage limit.

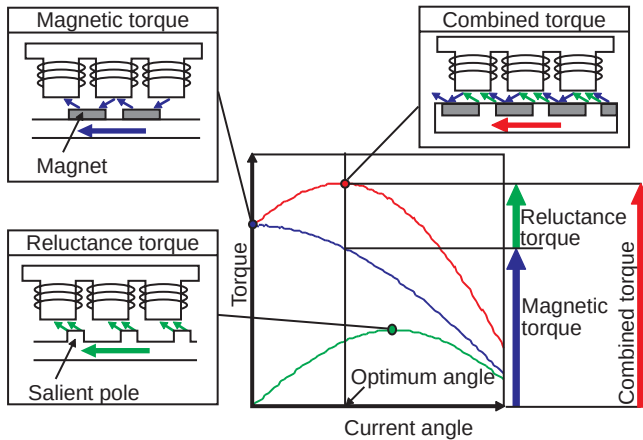


Fig. 6 Conceptual diagram of torque characteristic and current angle

$$P \propto \frac{V_b \cdot \phi a}{L_d} \quad (4)$$

3.3. Selection of Rotor Type

The type of rotor to be used in the MCF31 was selected in order to enable power and speed to be increased and size to be reduced against the MCF21.

It was necessary to optimize the inductance value in order to increase power and reduce size. L_d was set as the limit value (maximum) enabling the achievement of the target power when the motor was operating at maximum speed within the input voltage range. L_q was set in order to maximize the result of $(L_d - L_q)$, given the above condition. This would minimize the current required for field-weakening drive at high motor speed and enable reluctance torque to be used effectively, thus enabling the achievement of increased power and reduced size.

Achieving sufficient yoke strength is one issue in increasing rotor speed. At maximum speed, the weight of the magnets results in a strong centrifugal force being exerted on the yoke. It is necessary to achieve sufficient strength in the yoke to enable it to resist this centrifugal force.

With the goals set as optimization of the inductance value and the achievement of sufficient yoke strength, magnetic field analyses and strength analyses were conducted in order to compare the following two types of permanent magnet that have been successfully mass-produced:

Type A: Salient pole-type surface permanent magnet (SPM) used in the MCF21 motor [Fig. 7(a)]

Type B: Rectangular interior permanent magnet (IPM) with center rib used in the ACCORD Hybrid⁽⁶⁾ [Fig. 7(b)]

In type A, because the magnets can be positioned close to the stator core, the magnetic resistance on the d -axis

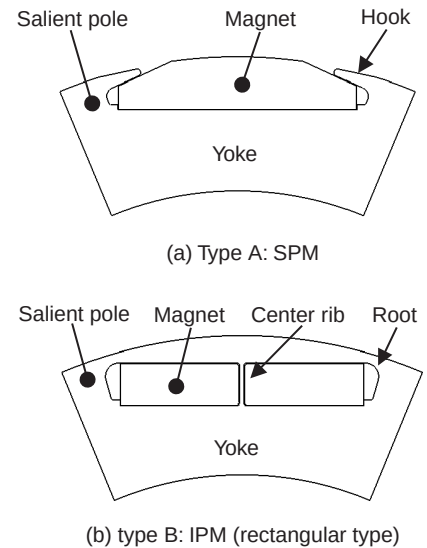


Fig. 7 Structure of rotor

can be increased, enabling L_d to be set low. In addition, (L_d-L_q) can be set high, and this type is therefore beneficial from the perspective of increased power. The results of the magnetic field analysis showed that the use of this type of rotor would enable the achievement of torque and power targets.

However, in addition to its higher speed, the reduction of the number of poles in the rotor in the MCF31 against the MCF21 would make it necessary to increase the amount of magnets per pole, resulting in a strong centrifugal force being exerted on the rotor yoke at maximum speed. The results of the strength analysis showed that stress would concentrate on the yoke hook sections that support the magnets, making it challenging to achieve sufficient strength at high speeds.

Type B divides the magnets in two by means of center ribs. The center ribs and the base of the yoke bear the centrifugal force that is generated, thus enabling excessive stress to be negated. The results of the strength analysis showed that optimum allocation of stress would enable sufficient strength to be achieved up to maximum speeds.

However, this type also reduces the magnetic resistance on the d -axis, thus increasing L_d , and the results of the magnetic field analysis showed that it would not enable the target power to be achieved at high speeds.

Based on the results discussed above, a type C was sought that would fuse the benefits of type A for high power and of type B for high speed.

Type C employed half-moon-shaped magnets to enable L_d to be set low, and used a center rib IPM configuration to enable the achievement of sufficient strength. A magnetic field analysis and strength analysis showed that type C would enable the target of a balance between high power and high speed to be achieved (Fig. 8), and an IPM rotor using half-moon-shaped magnets with center ribs was therefore adopted for use in the MCF31 (Fig. 9). Figure 10 shows the stress distribution on the magnets and the rotor yoke during rotor operation, as calculated in a nonlinear structural analysis.

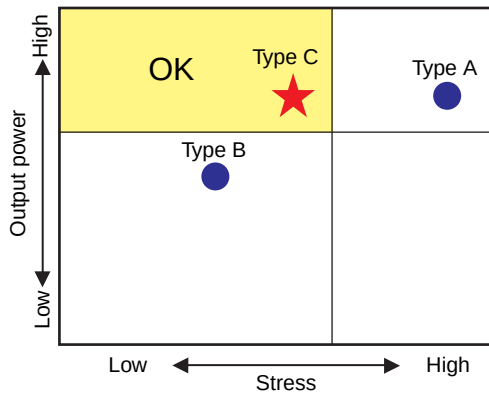


Fig. 8 Conceptual diagram of output power and stress and current angle

As detailed analysis of the half-moon-type IPM with center ribs proceeded, a new issue became apparent: Variations within the dimensional tolerance and variations in the mounting positions in the yoke slots resulted in considerable changes in the stress on the yoke at high speeds. This issue resulted from the fact that the employment of a unique half-moon shape as an IPM meant that the positions of contact between the magnets and yoke slots were unstable. The shapes of the magnets and yoke slots were therefore optimized to help ensure that the positions of contact would be stable, irrespective of the permutation of the dimensional tolerances and the mounting positions. As a result, fracture strengths of 23 000 min⁻¹ or more were achieved in fracture tests using actual rotors.

3.4. Responses to Magnet Heat Production and Surface Treatment

One of the characteristics of the Nd-Fe-B magnets used in the rotor is that their flux density declines as the temperature of the magnet increases. Because of this, as the temperature of the magnets increases with an increase in eddy currents at high speeds, the flux linkage of the magnets, ϕ_a , declines and maximum power also declines, following the relationship shown in Eq. (4)⁽⁷⁾. The upper limit for allowable magnet temperature can be determined from the motor power required in order to achieve maximum vehicle speed and the magnet temperature characteristic.

Heat generated by eddy currents produced in the interior of the magnets by changes in the magnetic flux in the rotor result in a marked increase in magnet temperature. In the MCF31, the magnets were divided in

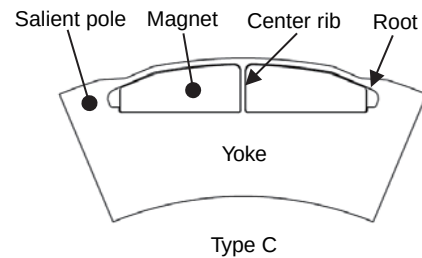


Fig. 9 Structure of IPM rotor (half moon type)

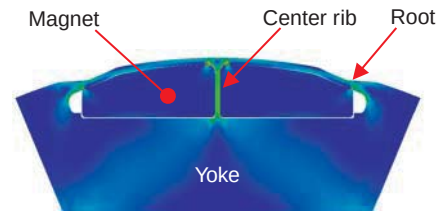


Fig. 10 Nonlinear analysis of IPM rotor (half moon type)

the axial direction and a plastic coating applied to their surfaces in order to reduce eddy currents. This has controlled the production of heat and kept the temperature of the magnets from exceeding the upper limit temperature, enabling the achievement of the power target.

Because the motor and gearbox have been integrated in the MCF31 in order to reduce the size of the drive unit, gear oil, used to lubricate the bearings of the primary shaft and drive shaft, is present in the motor. For this reason, in addition to insulation enabling eddy currents to be reduced and anti-corrosion performance, oil resistance was one of the qualities sought from the surface treatment applied to the magnets. An inorganic surface reforming treatment with superb oil resistance properties was therefore applied to the surfaces of the magnets, and the insulating surface treatment was applied over this treatment. Figure 11 shows the relationship between the number of divisions in the magnet and the target temperature, and Fig. 12 shows part of the divided magnet configuration inside the rotor.

3.5. Stator Cooling Technology

In order to help ensure a broad range of continuous operation, from hill-climbing to top speed, copper loss was reduced, and thermal resistance was reduced in the stator. Thermal resistance in the pathways for heat flow from the coils to the water jacket positioned on the outer circumference of the stator is known to be almost entirely dependent on the area of contact between the coils and the stator⁽⁷⁾. Eight poles have been employed in the rotor of the MCF31 in place of the 12 employed in the MCF21 in order to reduce motor loss. This reduced the area of contact between the coils and the stator, which increased thermal resistance and resulted in a decline in cooling performance. The ratio of the number of slots to the number of poles (n) was therefore increased from $3n$, as

in the MCF21, to $6n$ (Fig. 13) in order to reconcile the reduction of phase resistance (loss) with an increase in the contact area between the coils and the stator, enabling target cooling performance to be achieved.

This has enabled the temperature of the coils to be controlled to within the range of allowable temperatures

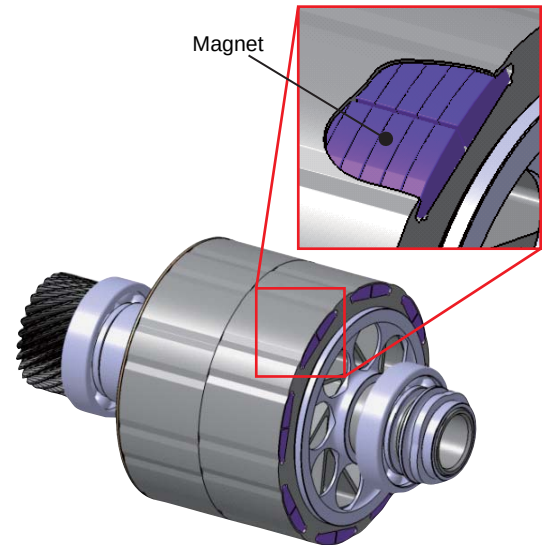


Fig. 12 Part of magnet division structure in rotor

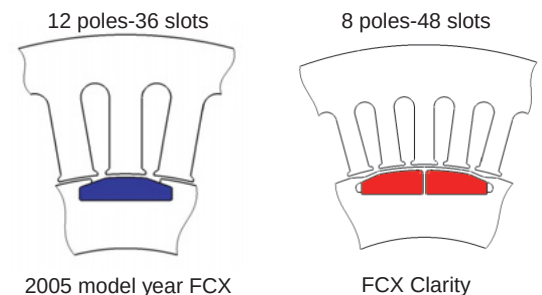


Fig. 13 Ratio of slots and poles

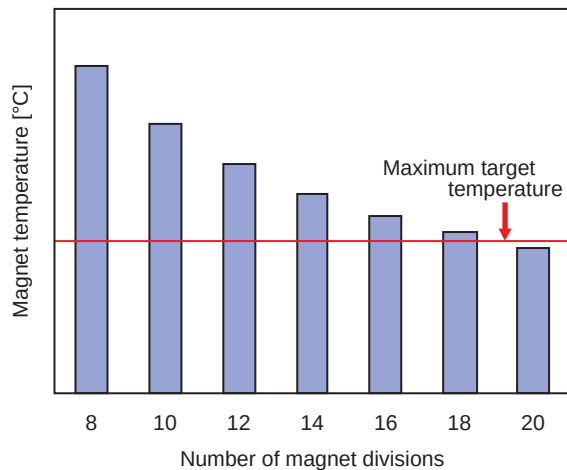


Fig. 11 Relation between number of magnet divisions and temperature

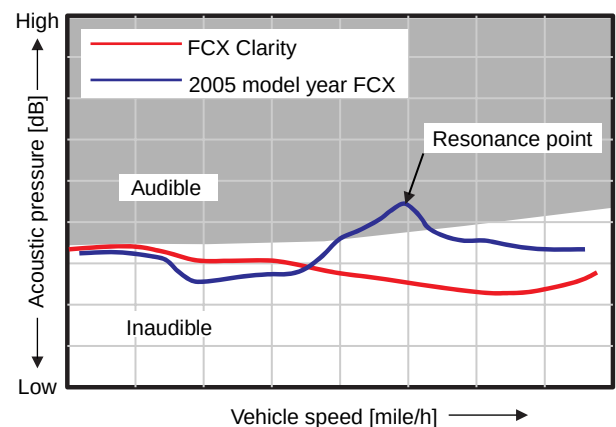


Fig. 14 Noise and vibration performance

for heat resistance in each section even when current is being continuously supplied when the vehicle is climbing a hill or the motor is being operated at maximum speed, conditions which represent a challenge for cooling.

3.6. Motor Noise and Vibration Performance

A level of noise and vibration performance was sought from the new motor that would enable the realization of the quietness only available from a motor drive – which features none of the vibration generated by reciprocating pistons or the combustion noise that characterize internal combustion engines - up to maximum speeds.

The use of eight poles in the MCF31 rotor in place of the 12 used in the MCF21 helped to eliminate resonance points in the use range of the motor (Fig. 14), enabling quietness to be reconciled with increased power.

4. Motor Performance

Table 2 shows the achieved performance of the MCF31. The motor's maximum efficiency is identical to that of the MCF21, but its torque density is more than 15% higher and its power density is more than 20% higher, while its weight is more than 20% lower.

4.1. Power

Test results indicated that the MCF31 motor achieves its target performance of a maximum power of 100 kW, maximum torque of 256 Nm, and maximum speed of 12 500 min^{-1} . The results are shown in Fig. 15. The range at which the motor's maximum power of 100 kW can be output extends from the mid-speed- (approximately 30 mile/h) to high-speed-range (approximately 80 mile/h), enabling the realization of take-off acceleration and passing acceleration performance equivalent to or higher

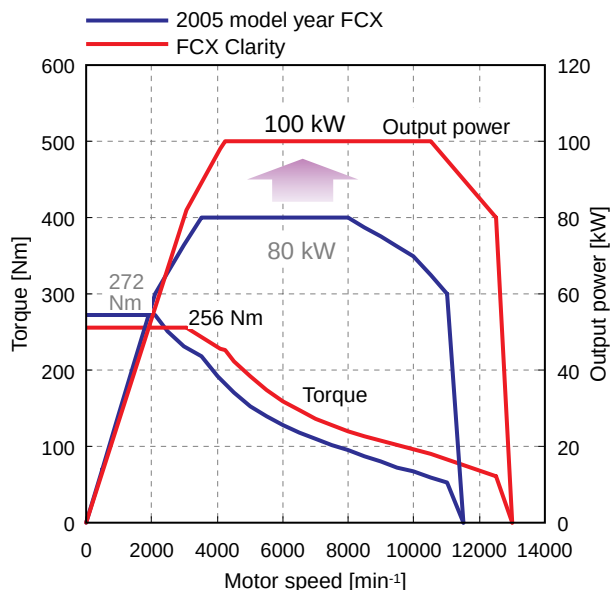


Fig. 15 Motor output performance

Table 2 Motor performance

Type	MCF21 (2005 model year FCX)	MCF31 (FCX Clarity)
Maximum power [kW]	80	100
Maximum torque [Nm]	272	256
Maximum speed [min^{-1}]	11000	12500
Maximum efficiency [%]	97	97

than those of a 2.4 L-class gasoline vehicle as shown in Fig. 16. In addition, as a result of the motor's outstanding cooling performance, the range for continuous rated output extends from hill climbing through city driving to top speed.

4.2. Energy Efficiency

With the achievement of a maximum efficiency of 97% during motor operation and a 36% reduction in drive unit friction loss, high efficiency operation has been realized in the drive unit. In addition, as Fig. 17 shows, optimization of energy management has enabled the

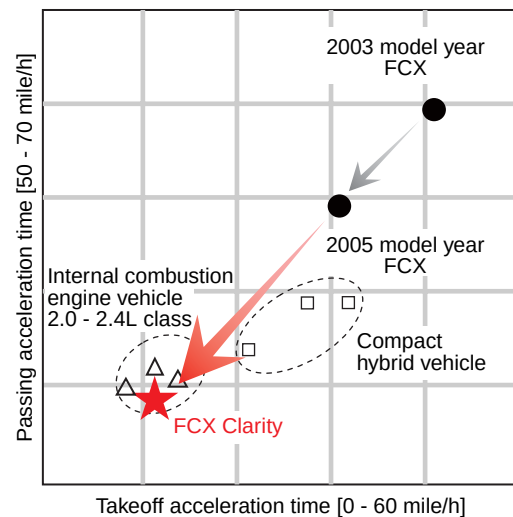


Fig. 16 Acceleration performance

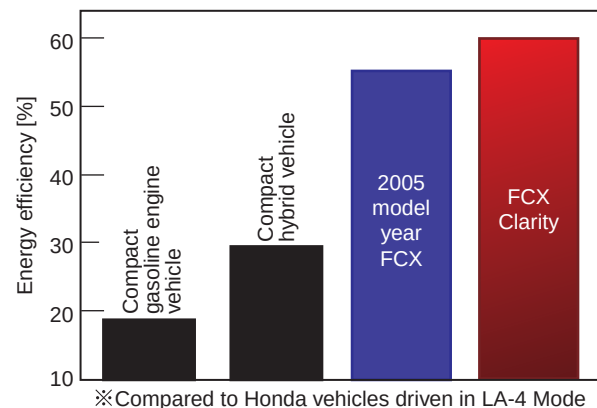


Fig. 17 Energy efficiency, LA-4 Mode

achievement of the target of an energy efficiency of 60%, approximately 10% higher than the 2005 model year FCX.

5. Conclusion

A drive motor was newly developed for the FCX Clarity, and has been employed in the vehicle. This development produced the following results.

- (1) Integrating the motor, gearbox, and power drive unit reduced the size of the drive unit, and enabled the realization of a design featuring a short nose and low overall height.
- (2) Increasing motor efficiency and reducing friction in the drive unit resulted in increased transmission efficiency, contributing to the achievement of an energy efficiency of 60%.
- (3) Reducing inductance in the motor enabled a power output of 100 kW to be maintained up to high speeds, enhancing the dynamic performance of the vehicle.
- (4) Increasing the strength of the rotor yoke enabled the rotor to be operated at higher speeds, resulting in the achievement of increased maximum vehicle speed.

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