

Development of the Motor for the Civic Hybrid

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ABSTRACT

A thin DC brushless motor was developed as auxiliary power for the Civic Hybrid, which is positioned to take the world lead in fuel consumption for five-passenger automobiles. The concept was to create a hybrid car using an existing mass-produced engine in an existing mass-produced car body. This raised more issues than the Insight, which was made with an engine and body specifically designed for that purpose. The Civic has a heavier body than the Insight. In order to assure its power performance and increase the energy regenerated during deceleration the engine displacement had to be increased and the regenerative performance of the motor had to be improved. However, the Civic body has the same width as the Insight, so it was not possible to increase the motor width in correspondence with the regenerative performance. The objective in development of the motor, therefore, was to improve performance while keeping the motor the same width. The methods used to achieve this objective were to increase the torque constant and to reduce the losses in all parts involved. Specifically, the space gained in the axial direction by functional integration of parts made it possible to increase the cumulative stator thickness, and the adoption of new coil winding methods made it possible to enlarge the coil diameter and the width of the teeth. As a result, the motor regenerative torque was improved approximately 30% while maintaining the same motor width, and the average efficiency of the motor in the practical use area was improved approximately 3%.

1. Introduction

In response to the demand for automobiles that are clean and consume less fuel, Honda began to market an ultra-low fuel consumption hybrid 2-seater car fitted with an IMA (Integrated Motor Assist) system in 1999 – the INSIGHT⁽¹⁾. In 2001, the CIVIC Hybrid was marketed, giving the 5 passenger, 4-door CIVIC an improved IMA system. The

motor in the IMA system provides assistance during acceleration and energy recovery during deceleration, and also provides for rapid engine start so that there is no feeling of uneasiness with the Idle Stop System. The motor fitted to the CIVIC Hybrid was developed to improve regenerative performance and at the same time be light weight and compact for productivity improvements. This paper introduces the motor technologies used to achieve these aims.

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2. Aims of Development

The developmental aims for the CIVIC Hybrid motor were the following three items and the realization of new functions.

2.1. Increase in Regenerative Torque and Improved Efficiency in the Practical Use Range

In comparison with the INSIGHT, due to an increase in car body weight and a reduction in engine friction through the adoption of a cylinder idling system, etc., there is an increase in deceleration energy that the motor can recover. This means it is necessary to improve the corresponding regenerative torque. Improving regenerative torque while leaving motor efficiency as it is would lead to an increase in loss. Furthermore, natural air-cooling would not be feasible, so in this case a new cooling system would be required. A new cooling system would cause other problems in terms of space, weight, and overall efficiency, eliminating some of the advantages of the hybrid system. This means it is necessary to increase motor regenerative torque while simultaneously improving efficiency in the wide practical use range. It is particularly important to reduce losses on the high load side.

2.2. More Compact

In comparison with the INSIGHT that had a specially designed engine and car body, the target for the CIVIC Hybrid was to use a compact mass produced engine and mass produced car body, meaning that a compact motor was essential. Specifically, the development targets were to improve efficiency and regeneration performance corresponding to the increase in deceleration energy without changing motor width dimensions, so that, in comparison with the INSIGHT's 3-cylinder 1.0 L engine, a 4-cylinder 1.3 L engine, having the same 1,695 mm width as the INSIGHT, could be fitted in the CIVIC car body.

2.3. Lighter Weight and Productivity Improvements

In order to achieve the improved fuel economy that was the target for the CIVIC Hybrid, efforts were made for overall vehicle weight reduction, and at the same time, weight reduction of the motor. In addition, to expand the potential use of the 5-passenger, 4-door CIVIC Hybrid body, it was necessary to make further productivity improvements.

The following sections of the paper explain the specific technologies developed to achieve these aims.

3. Increase in Regenerative Torque and Improved Efficiency in the Practical Use Range

In order to achieve the above aims, efforts were made to increase torque constant, in comparison with conventional motors, and at the same time to reduce energy loss in each part. Increasing torque constant is not simply a matter of improving regenerative torque, but also contributes to improving efficiency in the practical use range. Generally, when the torque constant is increased, it is possible to move the motor's high efficiency range towards the lower engine speed side. With a conventional motor applied to the CIVIC as it is, the motor's high efficiency range is slightly to the high engine speed side of the practical use range, as shown in Fig. 1. Therefore, increasing torque constant also leads to improvements in the practical use range efficiency.

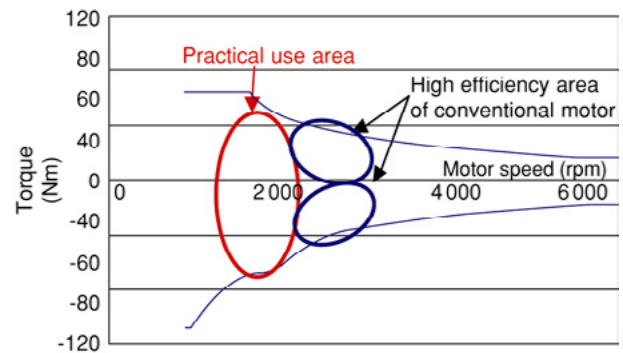


Fig. 1 10-15 Mode traveling area

3.1. Torque Constant Increase

An increase in torque constant is mainly accomplished by increasing the cumulative stator layer thickness (referred to as stator cumulative thickness hereafter). However, with a conventional structure, it is not possible to maintain axial direction space, so increasing the stator cumulative thickness was not possible. As explained in the paragraph below, thanks to functional integration of the parts inside the motor, it is now possible to maintain axial direction space, and so, as shown in Fig. 9, stator cumulative thickness has been increased by 13%. Mainly due to these modifications, torque constant could be increased by approximately 16% over the conventional model.

3.2 Reduction in Copper Loss, and Improved Saturation Flux Density

In order to reduce copper loss, the wire diameter was increased from 1.3 mm to 1.5 mm, reducing wire resistance by 33%. In addition, as shown in Fig. 2, the teeth width was increased, thereby improving saturation flux density, and by improving magnetic saturation during high torque generation, there is a reduction in loss in the high torque range.

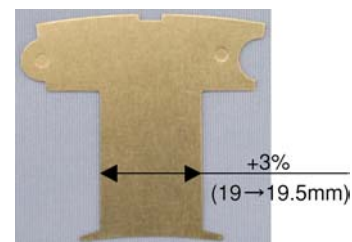


Fig. 2 Width of teeth

Here, if magnetic wire diameter enlargement and teeth width extension were carried out using conventional method, the thicker wire must be used in reduced space. Therefore, there would be a drastic reduction in the number of coils, causing a drop in performance. However, here we have applied a new winding method, as outlined below.

3.3. Asymmetric Winding

As shown in Fig. 3(a), if the wire is wound on teeth covered with a completely uniform insulator thickness, the coil becomes thicker in the middle, and will contact the adjoining coils. By taking countermeasures so that the winding does not accumulate in the center, even when using

wire with a thicker diameter the number of coils can be maintained. Specifically, the method is, as shown in Fig. 3(b), to have asymmetric insulator thickness, so that the thick part of the coil is not in the center, and that the coils are offset so that they don't come in contact each other. This means that it is possible to increase the wire diameter and widen teeth diameter without causing a drop in performance.

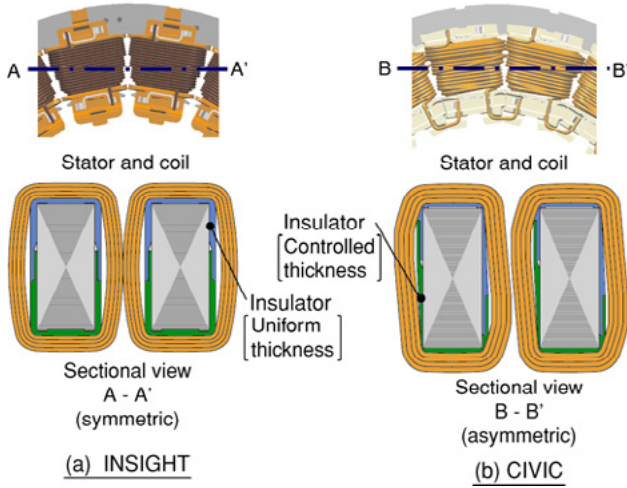


Fig. 3 Comparison of stator and coil

3.4. Revision of Silicon Steel Stamping Direction

Revision of silicon steel stamping direction was carried out to further improve performance. Generally, when non-directional silicon steel is used, there is no difference in properties due to direction, so stamping is carried out giving priority to yield. In addition, with a separated stator, in particular the teeth part and the back yoke part magnetic flux flow directions are straight so there are no restrictions in stamping direction.

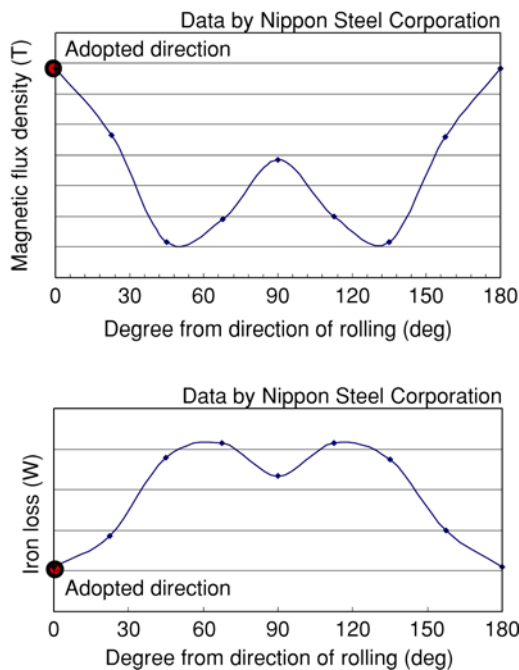


Fig. 4 Magnetic flux density and iron loss

However, even with non-direction silicon steel, as shown in Fig. 4⁽²⁾, there are small differences in properties due to direction. A detailed analysis was made of the amount of magnetic flux in each part of the stator for this motor, and of direction, as shown in Fig. 5, to determine optimum stamping direction. From the results of this study, priority is given to the flow of magnetic flux in the teeth, and as shown in Fig. 6, it is clearly best that the motor diameter direction and rolling direction match, so this was adopted. As a result, it is possible to improve, by approximately 1.5% over the conventional design, efficiency that leads to improvements in electromagnetic saturation in the low engine speed high torque range, and to a reduction in iron loss.

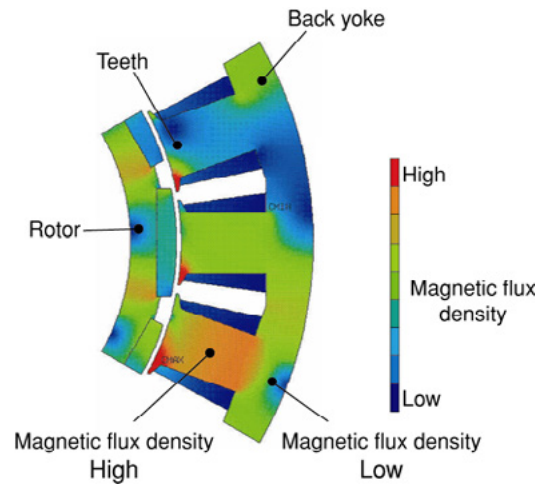


Fig. 5 Simulation of magnetic circuit

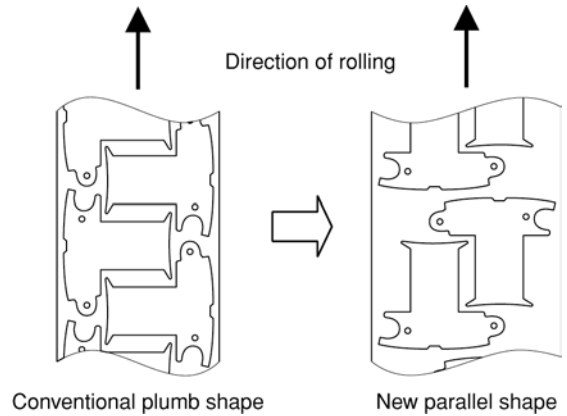


Fig. 6 Shape of stamp working

3.5. Summary of Increases in Regenerative Torque and Improvements in the Practical Use Range Efficiency

By carrying out the measures outlined above, as shown in Fig. 7, maximum regenerative torque is 30% better than with the conventional model, and with motor efficiency improvements (Fig. 8), average motor efficiency in the practical use range was improved by approximately 3%.

Major motor specifications are given in Table 2.

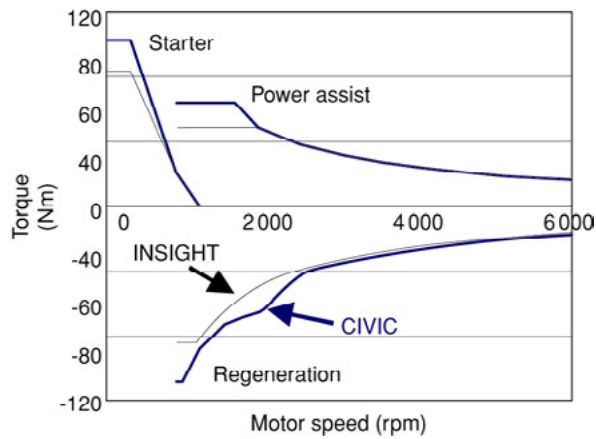


Fig. 7 Motor performance curve

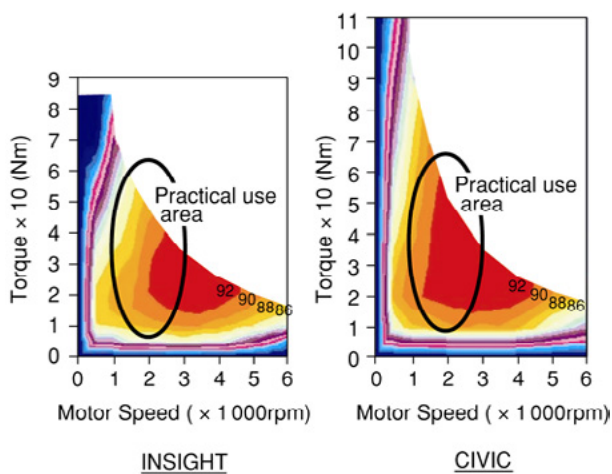


Fig. 8 Motor efficiency

Table 2 Motor specification

Motor type	DC brushless	
	(1) Power assist	(2) Regeneration
Max power	10kW	12.4kW
Max torque	49Nm (103Nm at engine Start)	108Nm

4. More Compact

In order to maintain motor width while making regenerative torque and efficiency improvements, functional integration of parts inside the motor was carried out, and axial direction space was reviewed. Space was created by eliminating the resin cover that, in the conventional structure, functions to hold the bus ring and the silicon plastic injection-molding frame for the coil connected insulation. When the resin was eliminated, as for bus ring holding, the structure was changed so that each separate part is an integrated part, able to support itself. As for the injection-molding frame function, the clearance with the adjoining insulator was created so that the silicon plastic cannot flow in, and a framework was formed by the bus ring around the outside and insulator around the inside.

Due to these measures, as shown in Fig. 10, motor width was not changed but stator cumulative thickness was increased by approximately 13%.

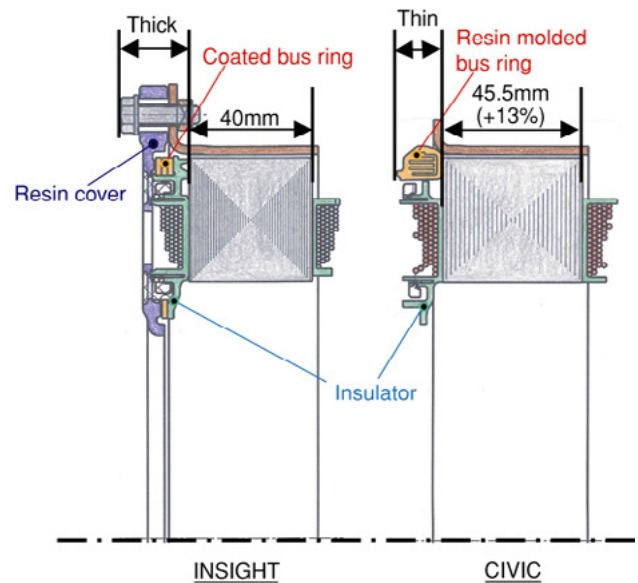


Fig. 9 Cutaway view of stator

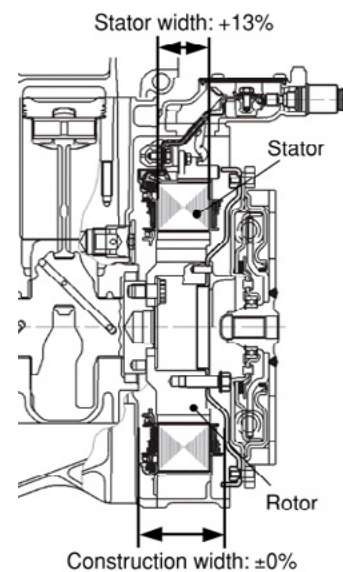


Fig. 10 Cutaway view of motor

5. Weight Reduction and Productivity Improvements

5.1. Sinter Diffusion Bonded Rotor

As shown in Fig. 11, the rotor has two functions – the outside functions to hold the magnets and create the magnetic circuit, while the inside functions to transfer torque between the crank and the transmission. Conventionally, carbon steel is selected, to make the torque transfer function feasible. The lost wax manufacturing method is adopted as the most appropriate when using this material. In contrast, the adoption of sinter diffusion bonding, which makes it possible to combine two materials having different properties that are

necessary for the functions on the inside and the outside, means that it is possible to use a high strength material on the inside, while using a soft magnetic material on the outside. While material density drops and connection strength is maintained, saturation flux density is improved by 30%. This leads to improved performance and a 15% reduction in weight.

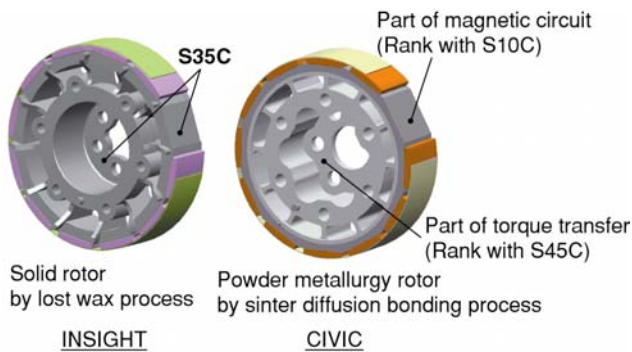


Fig. 11 Rotor construction

5.2. Resin Molded Bus Ring

The performance demanded of a bus ring is to make the distribution of electricity to each layer feasible, while providing insulation between each layer and GND insulation. As shown in Fig. 12, a conventional bus ring is coated with insulation in each layer, and during stator assembly, the structure deals with each one individually. In contrast, by using float-molded resin molding technology, it is possible to integrate all three parts into one, dramatically improving productivity.

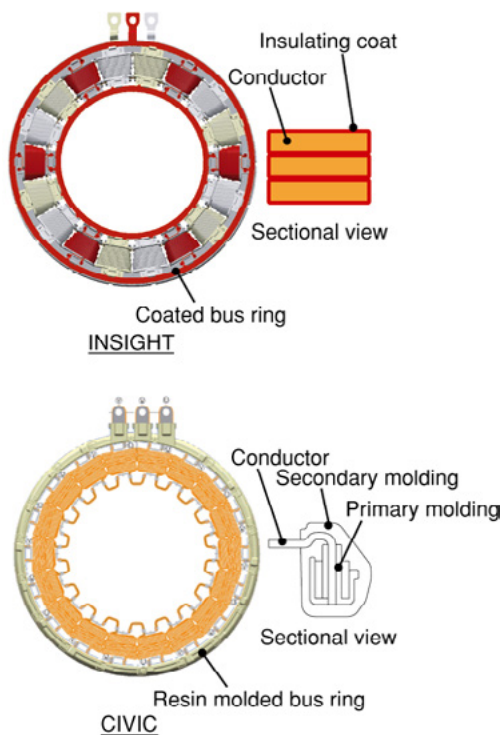


Fig. 12 Bus ring construction

This bus ring structure maintains the mutual insulation function with the primary molded body, and maintains GND insulation with the secondary molded resin. For this reason, it is necessary that the secondary molded resin completely envelop the primary molded body. The primary molded body floats in the mold on a support pin which is removed according to the resin hardening timing, and the resin completely fills the mold, so that no signs of the pin remain. By adopting this technology, insulation performance is maintained, and at the same time, manufacturing and assembly time is reduced by approximately 50%, achieving a dramatic improvement in productivity.

5.3. Neutral Point Direction Wiring

Conventionally, as shown in Fig. 13, a neutral point bus ring was used for each part, and these were connected. In contrast, without using a special bus ring, the structure is such that neutral points are formed with the wires. Specifically, using a salient-pole concentrated winding method on the separate teeth, it is possible to maintain a wire length the same as the distance to the adjoining neutral point, and when fusing to the bus ring, on the neutral point side, too, there is fusing between neutral points. Through this, the neutral point bus ring is eliminated, the structure is simplified, and weight is reduced.

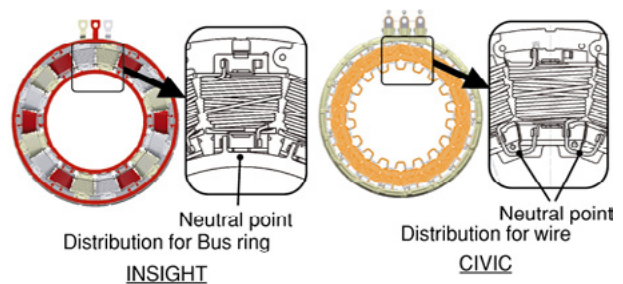


Fig. 13 Neutral point construction

6. New Function

With the CIVIC Hybrid, one developmental target is to achieve smooth driving by utilizing a motor assist function. The following is an explanation of newly applied functions to actualize that smooth driving.

6.1. Reduction in Vibration during Deceleration by Employing Motor Control

In order to achieve smooth driving, the vibration control technology used in the INSIGHT during idling has been more widely applied to deceleration. Specifically, the vibration reduction technology reduces vibration by utilizing a direct crankshaft to motor connection that is a feature of the IMA system, generating phase torque in the motor that is the reverse of the engine torque generated during deceleration. At this time, the amount of torque generated is determined by engine speed and load, and based on the crank position signal the torque phase is determined from engine speed and load.

The effectiveness of this control is shown in Table 1 and Fig. 14.

Table 1 Effect of damping control

Measuring point	Effect
Floor vibration	-6dB
Engine vibration	-4dB

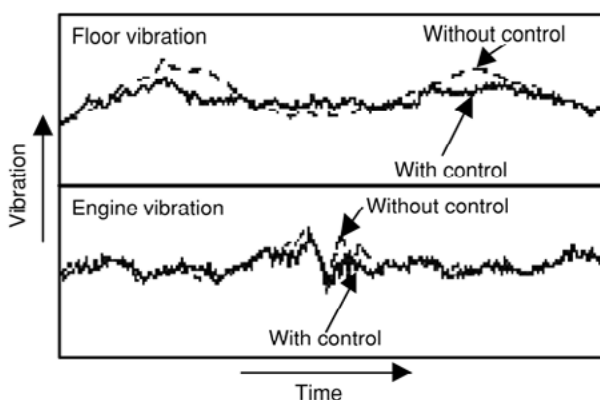


Fig. 14 Vibration in deceleration

6.2. Reduction in the Car Body Jerky Feeling through Motor Control

As another new function, the motor control is used to reduce the car body jerky feeling through throttle control when driving a manual transmission equipped car in low gear. Specifically, as a method of reducing vibration and utilizing the direct motor connection to the crankshaft in the same way as in the vibration control system, motor torque is applied at an appropriate time in response to car body longitudinal vibration generated according to throttle opening changes, and the jerky feeling is restricted. At this time, assistance or regeneration is determined from the direction of throttle change, and the amount of applied torque and the timing is determined from the amount of change in engine speed. The effect when this control is applied is shown in Fig. 15.

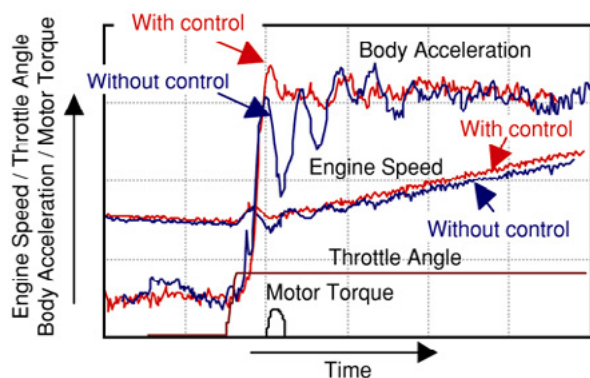


Fig. 15 Effect of smoothing control

7. Summary

In order to achieve the target performances set for the CIVIC Hybrid's motor, the torque constant was increased, and loss was reduced for each part. Specifically, maintaining axial direction space through the functional integration of parts made possible an increase in stator cumulative thickness. Furthermore, by adopting a new winding method, both wire diameter and teeth width were also increased. As a result, the developmental targets to improve drivability became possible, and at the same time, motor regenerative torque was improved by approximately 30% while retaining the same motor width, leading to an average efficiency improvement of 3% in the practical use range.

References

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