# Starting System for Stop/Start with Change of Mind

**Koichi Osawa and Hideya Notani**

**Abstract** Further fuel consumption improvement of stop/start vehicles can be achieved by expanding the fuel cut period. In order to maintain vehicle response, ability to restart the engine during an engine stop event, known as change of mind (CoM), is necessary. Two current technologies to enable CoM are belt driven starter generator and permanently engagement starter. Both these technologies, however, require modification to additional vehicle components. The conventional pinion-shift-type starter has constant timing between pinion movement and motor rotation. If applied to CoM, the conventional starter risks making a loud noise or suffering serious mechanical damage during pinion engagement into the rotating ring gear of the engine and so is considered as unacceptable. Theses issues can be solved by using a new pinion-shift-type starter, which has independently controllable pinion movement and motor, and starter operation control, which can change the starter operation depending on engine speed. Furthermore, engine speed prediction based on engine rotational energy gives more accurate starter operation control which improves noise and restart response. The new pinion-shift-type starter and starter operation control with engine speed prediction has been fitted to vehicles and the performance compared to conventional starter systems. It is confirmed that engagement noise for CoM restart is equivalent to normal start engagement and that restart response is faster than current starting system with conventional starters. In this paper, details of the newly developed starter and starter control are described, together with performance of the new starting system.

**Keywords** Stop/start · Fuel consumption · Change of mind · Starter · Engine speed prediction

F2012-D02-010

K. Osawa (✉) · H. Notani
DENSO Corporation, Kariya, Japan
e-mail: koichi_osawa@denso.co.jp

SAE-China and FISITA (eds.), *Proceedings of the FISITA 2012 World Automotive Congress*, Lecture Notes in Electrical Engineering 194,
DOI: 10.1007/978-3-642-33829-8_21, 

# 1 Introduction

Recently, many low fuel consumption technologies, such as hybrid and stop/start, have been introduced in the market to reduce $CO_2$ emissions. Stop/start is a particularly attractive technology for fuel consumption improvement because it can be easily installed on the existing vehicles. On stop/start vehicles, further fuel consumption improvement can be achieved by expanding the fuel cut period. Current stop/start vehicles cut the fuel after the vehicle has completely stopped. Therefore, cutting fuel before the vehicle stops will save more fuel than the current system. In the case of fuel cut timing at 20 km/h, the simulation result is shown in Table 1. An additional 3 % improvement in fuel consumption is expected due to expanding the fuel cut on a 2.0 L gasoline, automatic transmission vehicle over the NEDC (New European Driving Cycle). However, restart response requirements during engine run down (i.e. engine stopping), which is called change of mind (CoM), will increase as shown on Fig. 1, because the vehicle is still decelerating. In the case of CoM, it is important to maintain driveability by restating the engine as soon as possible. Therefore, a starting system is required to restart an engine when it is sopping. Currently, belt driven starter generator and permanently engagement starter can restart engine at CoM event. Both these systems, however, require vehicle components modifications and such modifications make these technologies less attractive to vehicle manufacturers. This paper describes the details and performance of a new starting system, consisting of a newly developed starter, based on conventional pinion-shift-type starter, and added starter control.

# 2 Subject of CoM Restart by Pinion-Shift-Type Starter

A conventional pinion-shift-type starter has one solenoid which moves the starter pinion gear forward and also closes the contacts to energize the motor. Therefore, the delay time from pinion movement to motor rotation is fixed, and the motor is rotated just before the pinion engages into the vehicle ring gear completely. When the ring gear is rotating, this fixed behaviour can prevent smooth engagement. This is more notable if the motor is energizing at high engine speed when the relative speed between pinion and ring gear is large. The impact of the pinion and ring gear engaging with a large relative speed can cause a loud noise during engagement. In addition, engine oscillation can cause the engine to go in reverse direction just before stopping. If the motor is energized during engine reverse rotation, a large impact will occur during engagement, and this can cause serious damage to the ring gear and starter.

To prevent these undesirable phenomena described the above, it is important to control the pinion engagement with the ring gear when the relative speed is in the desired range as shown in Fig. 2. The desired operation at different condition is described below:

**Table 1** Simulation results of fuel consumption improvement ratio

| | Conventional | New |
|---|---|---|
| System function | Engine stop during vehicle stop | Engine stop during deceleration vehicle speed: 20 km/h |
| Fuel consumption improvement by simulation (2 L Gasoline) | **NEDC** Automatic transmission 4.5 % | **NEDC** Automatic transmission 7.5 % |

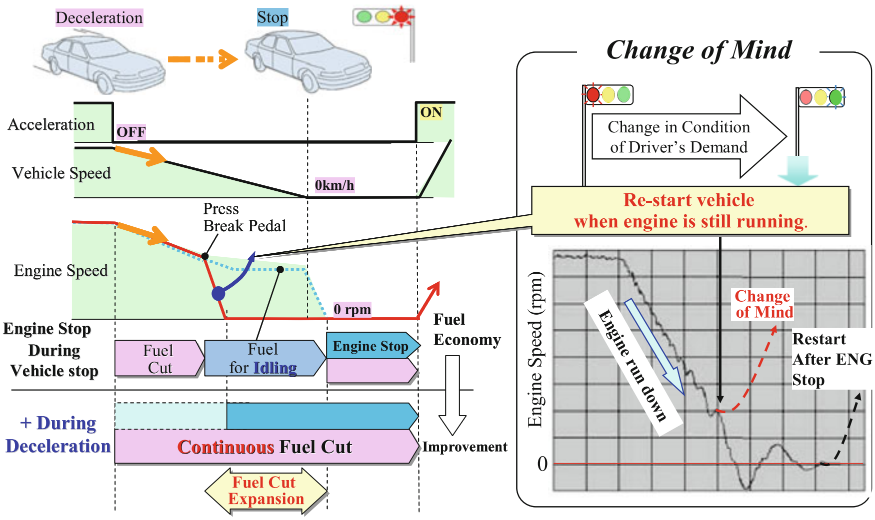


**Fig. 1** Necessity of change of mind (CoM)

a. At high engine speed: Motor rotation before pinion touch

At first, energize the motor to increase pinion speed, then move the pinion when the speed difference between the pinion and the ring gear is within the desired range. When the pinion contacts the ring gear, a relative speed difference of 0–200 rpm will ensure smooth and stable engagement.

b. At low engine speed: Motor rotation after pinion touch

At first, move the pinion, then energize the motor after complete engagement.

c. At engine reverse rotation: Pinion pre-engagement

Even though engine restart may not be required, move the pinion just before engine rotation direction changes to reverse, then engage completely. Then if a CoM restart is required during engine reverse rotation, the pinion is already engaged, and so the starter can crank the engine by just energizing its motor.

To realize the above operation, the following two are required.

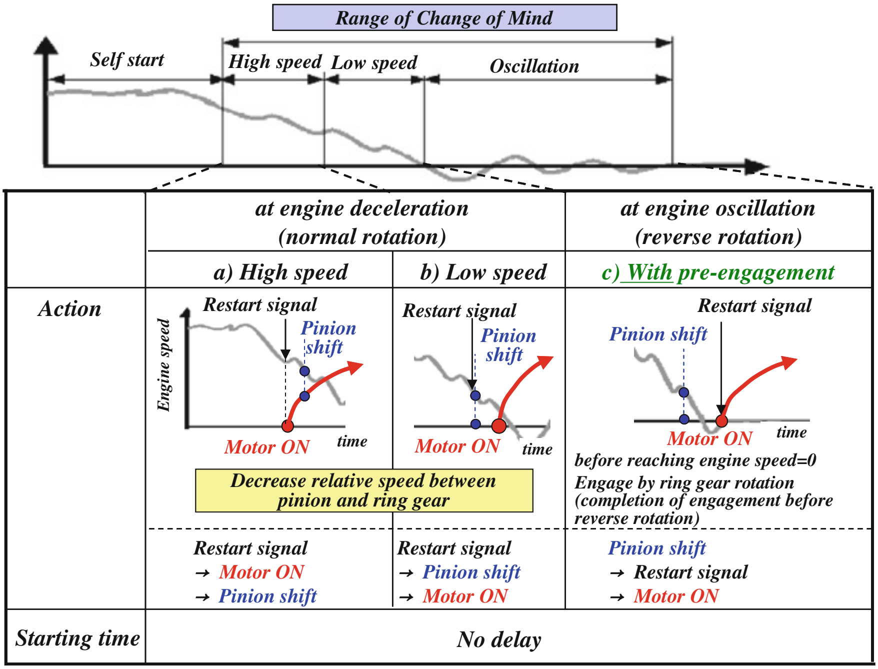


**Fig. 2** Operation of CoM

- a pinion-shift-type starter which can move the pinion and energize the motor independently
- a starter operation control which can operates the starter with accurate timing

To operate the starter at accurate timing, it is necessary to accurately determine the engine speed when the pinion engages into the ring gear. However, the pinion-shift-type starter always has some clearance between the pinion and the ring gear to avoid interference during engine running. Therefore, there is a time delay from when the pinion starts moving to contact with the ring gear. In addition, the engine speed determined by crank angle sensor has a greater error at lower speed. This error may increase during the time delay between start of pinion movement and pinion contact with the ring gear. Therefore, the starter operation control needs to have the following function:

- Predict the future engine speed accurately.
- Start moving the pinion at the correct timing to ensure that the relative speed at contact of the pinion and the ring gear is within the desired range.

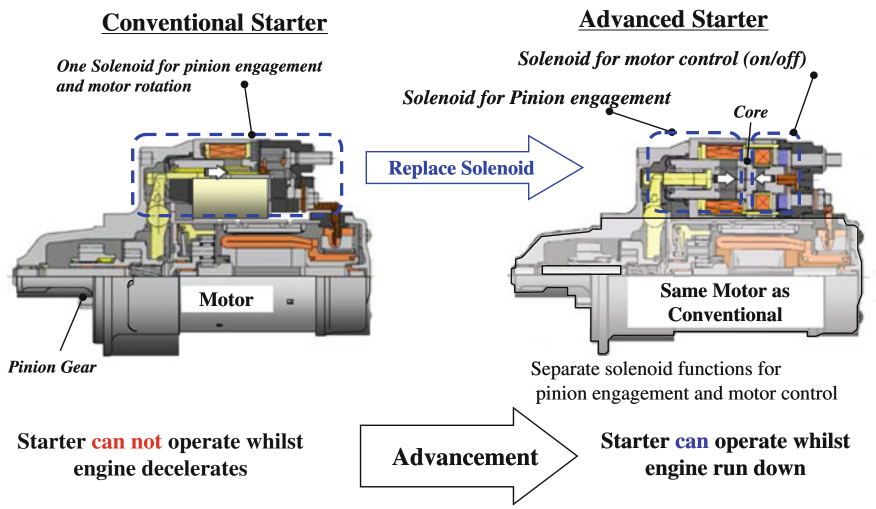


**Fig. 3** Advanced starter corresponding to CoM

# 3 New Starter for CoM

## *3.1 Structure*

The newly developed starter is shown in Fig. 3. To realize the operation shown in Fig. 2, this starter has two independent solenoids: one to move the pinion gear, and the other to energize the motor. These two solenoids are located along the same axis, and share the same core since both plungers operate in opposite directions. This arrangement helps to reduce the whole solenoid length. The rest of the structure and components are the same as a conventional starter. As a result, the change in starter packaging on the vehicle compared to a conventional starter is minimized.

## *3.2 Engagement Mechanism into Rotating Ring Gear*

The engagement mechanism of the pinion into the rotating ring gear (positive direction) is shown in Fig. 4. The preconditions are that the relative speed between the pinion and the ring gear is 0–200 rpm, and that the starter motor stars to apply its torque only after complete engagement.

After the pinion moves and contacts with the ring gear, the pinion chamfer and the ring gear chamfer are in contact. Even though the pinion contacts with the ring gear at each edge surfaces first, the contact surface moves to the chamfer because the ring gear is rotating and the pinion is pushed by the starter solenoid force.

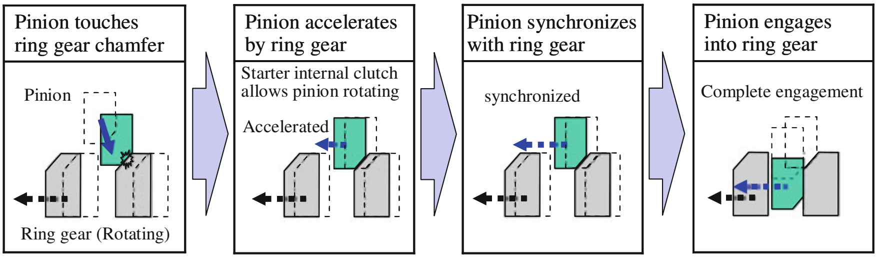


**Fig. 4** Mechanism of starter pinion engagement with rotating ring gear

The ring gear rotating force is transferred to the pinion through the chamfer, then the pinion starts rotating and accelerating. The starter contains an overruning clutch, therefore, it allows the pinion to rotate with little friction. Since the ring gear speed is also decelerating, its speed tends towards the pinion speed. When the pinion speed matches with the ring gear speed, the pinion will engage completely into ring gear.

# 4 Starter Operation Control

## 4.1 *Key Phenomenon for Engine Run Down Speed Prediction*

After fuel cut, the engine speed runs down with oscillations due to the repeated intake and compression of the engine cylinders. This engine run down behaviour is affected by many factors such as coolant temperature, engine oil viscosity, engine friction change due to aging and mechanical loads of auxiliaries, and so on. Therefore, the engine speed prediction based on the actual engine condition is necessary to accurately determine the engine speed.

The engine run down behaviour depends on mechanical losses, therefore the kinetic energy change of the engine is considered. After fuel cut, the engine speed decreases due to losses in rotational energy by pumping losses, friction losses, and mechanical losses of auxiliaries as shown in Fig. 5. Each loss is assumed as almost constant below idle speed [1]. Based on these phenomena, the future engine speed can be predicted from rotational energy change from previous stroke. The details of prediction method are described below.

## 4.2 *Engine Run Down Speed Prediction*

### 4.2.1 Mechanism of Engine Run Down

The energy change of crank angle change $(\theta_i \rightarrow \theta_{i+1})$ at engine stroke number $(j)$ is calculated by the following equation.

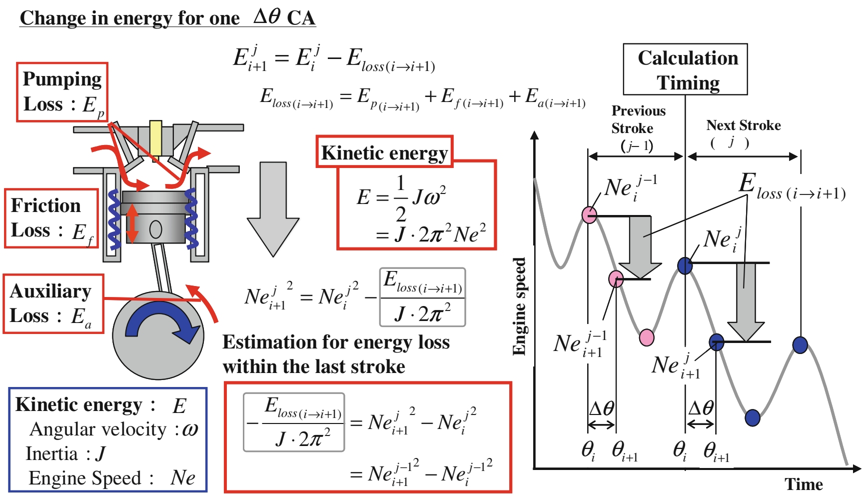


**Fig. 5** Mechanism of engine deceleration

$$E_{i+1}^{j} = E_{i}^{j} - E_{loss(i \to i+1)} \tag{1}$$

where, $E_{loss}$ is the combined losses of pumping losses, friction losses, and mechanical losses of auxiliaries. The rotational energy of engine $E$ is defined by the following equations:

$$E = \frac{1}{2} J\omega^2 = J \cdot 2\pi^2 Ne^2 \tag{2}$$

where, $J$ is engine inertia, $\omega$ is angular speed, $Ne$ is engine speed.

Equation (1) can be rearranged in terms engine speed $Ne$ as below:

$$Ne_{i+1}^{j2} = Ne_{i}^{j2} - \frac{E_{loss(i \to i+1)}}{J \cdot 2\pi^2} \tag{3}$$

Assuming each loss is constant against engine speed, the relationship between the engine speed at engine stroke $(j - 1)$ and the engine speed at the same crank angle after one stroke $(j)$ is given by the flowing equation:

$$-\frac{E_{loss(i \to i+1)}}{J \cdot 2\pi^2} = Ne_{i+1}^{j2} - Ne_{i}^{j2} = Ne_{i+1}^{j-1^2} - Ne_{i}^{j-1^2} \tag{4}$$

## Engine Run Down Speed Prediction

From Eq. (4), the difference of the squares of the engine speed at the last stroke $(j - 1)$, and the engine speed at the calculation timing, the engine speed $\hat{Ne}_{i+1}^{j}$ and time $\Delta\hat{t}_{i+1}$ at next crank angle (after $\Delta\theta$) are given by the following equations:

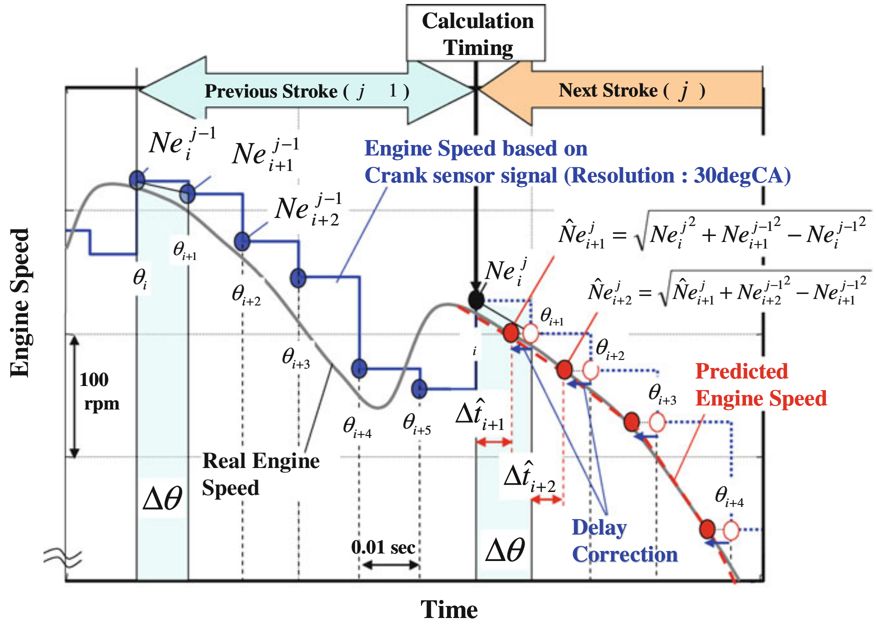


**Fig. 6** Engine speed prediction

$$
\begin{aligned}
\hat{N}e^{j}_{i+1} &= \sqrt{Ne^{j^2}_{i} + Ne^{j-1^2}_{i+1} - Ne^{j-1^2}_{i}} \\
\Delta\hat{t}_{i+1} &= \alpha \frac{1}{3} \frac{\Delta\theta}{(Ne^{j}_{i} + \hat{N}e^{j}_{i+1})}
\end{aligned}
\tag{5}
$$

where, $\alpha$ is the correction coefficient for time delay.

Typically, the engine speed is calculated from pulse output of the crank angle sensor. Therefore, the time delay will be longer due to slower response at low engine speed. It is possible to predict the engine speed more accurately by correcting this delay. Repeating the calculation of the engine speed at next crank angle based on Eq. (5) will give the predicted engine run down behaviour (Fig. 6).

## Confirmation Results on Actual Vehicles

The relationship between predicted engine speed and measured engine speed is shown in Fig. 7. The predicted engine speed is calculated from the engine speed measured by crank angle signal with 30 degCA resolution (in order to avoid the missing teeth). The measured engine speed is determined from an angle encoder signal with 0.5 degCA resolution. One of the test vehicles is a 3 cylinder petrol engine which has large oscillations during run down, and the other vehicle is the diesel engine which has a high compression ratio. The predicted engine run down

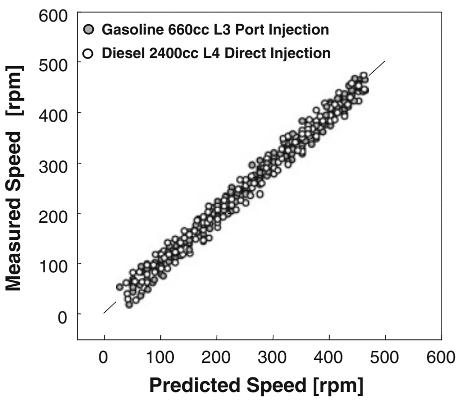


**Fig. 7** Test result of engine speed prediction

speed is selected 50 ms later from calculation timing as time delay correction in this case. As shown in Fig. 7, the predicted speed agrees closely with the measured speed.

This prediction method improves the robustness of the predicted speed by using the latest measured speed, and updating the predicted speed at each 30 degCA, so preventing an accumulation of errors and adopting to changing conditions.

# 5 Merit of Developed Starting System

## *5.1 Engagement Noise*

Figure 8 shows the relationship between the engine speed at restart and the engagement noise measured at 1 m from the vehicle front. The test vehicle has a three cylinder petrol engine which results in large oscillations during run down. In the case of no speed prediction, the starter control logic has to include various factors which affect engine run down behaviour variation. The starter trigger timing is sometimes earlier than proper timing due to such variation. In addition, the relative speed between the pinion and the ring gear are larger than expected. The engagement noise depends on the relative speed between the pinion and the ring gear. Therefore, the engagement noise is larger than normal engagement noise. On the other hand, the engine speed prediction improves the relative speed between the pinion and the ring gear as expected. As a result, the engagement noise variation is equivalent to the noise level of normal starter engagement into a stationary ring gear.

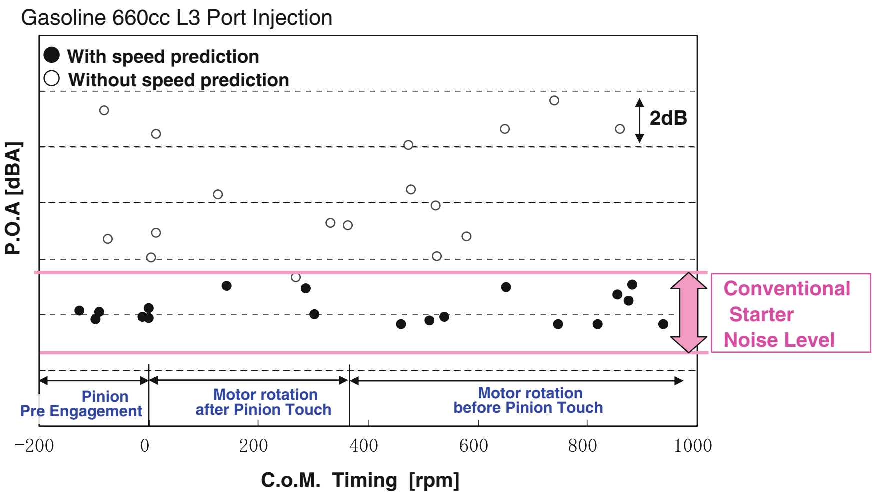


**Fig. 8** Noise level at engine start

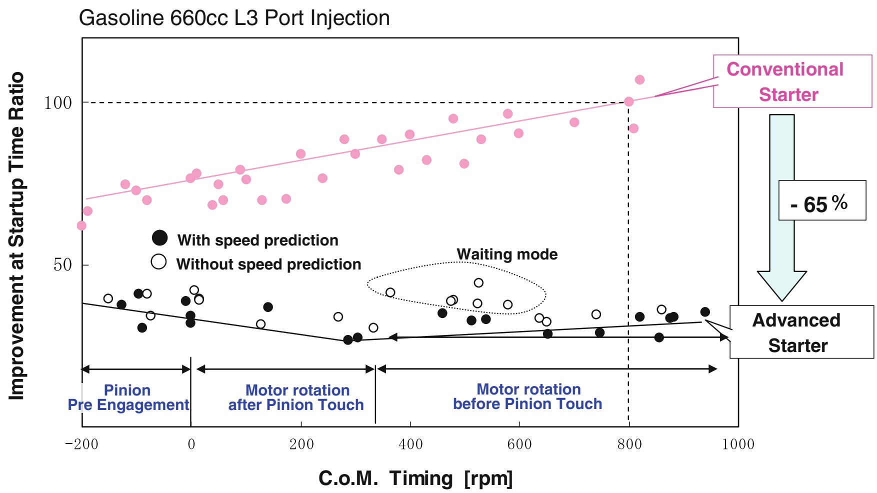


**Fig. 9** Improvement at startup time ratio

## *5.2 Starting Response*

The starting response improvement using the new advanced starter for different engine speeds at CoM requirement is shown in Fig. 9. In the high engine speed area, the start-up time is longer at higher CoM requirement speed because of the acceleration time of the pinion speed by the motor. In the low engine speed area, the start-up time is a minimum at the point that the engine speed is equivalent to the starter cranking speed. This is because the starter does not need to crank the engine against its rotational inertia. At lower speed, the starter needs to crank the engine against its inertia, therefore, start-up time is longer.

Without speed prediction, the starter trigger timing cannot be optimised for all situations and so sometimes enters a waiting mode until changing the starter operation mode to "motor rotation after pinion touch" which impacts on system response time. As a result of the speed prediction, the ratio of start-up time improvement against conventional starter is approximately 65 %.

## 6 Conclusion

A new starting system for CoM has been developed with the following features: a new pinion-shift-type starter with independently controllable pinion movement and motor; starter operation control with engine speed prediction. With this starting system, it is confirmed that the engagement noise at CoM is equivalent to normal cranking noise with a conventional starter. In addition, the starting response is better than current starting systems using a conventional starter on a vehicle.

## Reference

1. Hiroyuki H, Yukio H, Yoshishige O (1986) Internal combustion engine (Japanese). CORONA Publishing Co., Ltd, pp 72–76