Development of the world's first CVT sailing stop for the European market

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Abstract

For the first time, a sailing-stop technology was adopted by Jatco CVT-X, in combination with CVT, for the European market.

In recent years, European manufacturers and suppliers have actively adopted it for the purpose of CO_2 reduction and improved fuel efficiency. However, although the technology can serve the intended purpose, it is necessary to make compatible with drivability performance during re-acceleration.

This paper explains in detail how the world's first sailing-stop technology that utilizes the features of the Jatco CVT-X has achieved drivability performance during re-acceleration.

1. Introduction

Recently, although carbon neutrality has been realized through the electrification of vehicles, continuous CO_2 reduction has also been aimed at for ICE. From 2020 to 2024, the CO_2 reduction target in Europe is 95 g CO_2/km based on the emission test method, and there is a high penalty of 95 € per 1 g/km of excess emissions. However, there is a preferential treatment called an eco-innovation system that grants the right to vehicles equipped with innovative technologies for controlling CO_2 emissions, for which CO_2 reduction cannot be completely verified. Particularly, among European manufacturers, car models that adopt the sailing-idle function in combination with DTC and AT have become commercially available; thus, sailing-stop technologies are increasingly needed.

Because the CVT can carry out a highly flexible stepless shift even at a sailing stop, it has a technical value in that it can control the precise driving force intended by the driver and realize stable re-acceleration performance.

This study introduces the sailing-stop technology developed by Jatco CVT-X (CVT-X) for the European market.

2. Outline

The sailing stop is a control in which the engine is stopped while coasting a vehicle, and the clutch between the engine and transmission (T/M) is separated (Fig. 1).

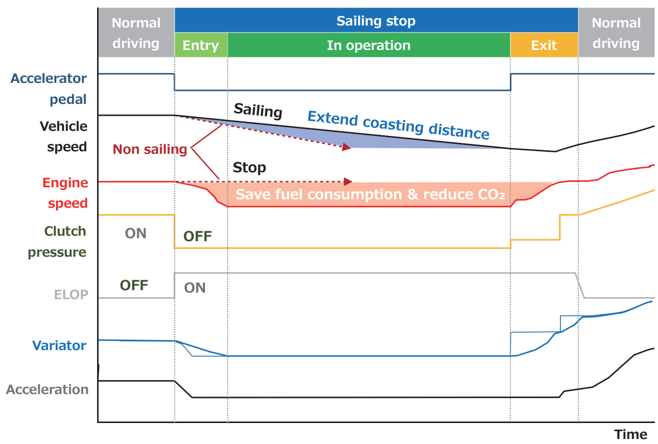

Fig. 1 Sailing stop control outline

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Sailing extends inertial running distance. therefore, the gradually decelerating speed reduces the driver's unnecessary accelerator pedal operation, and the engine operation time can be reduced.

The activate range of the vehicle speed is wide from high to low, as in the case of highways and urban driving, and the sailing stop is activated when the accelerator pedal is released.

The engine is stopped during the activation of the sailing stop, but a clutch release and variator shift are required for T/M.

The oil flow rate must adapt to rapid shifting of variator, such as sudden heavy braking, road surface input, and re-acceleration. The CVT-X adopts a twin oil pump system, and at the sailing stop, electric oil pumps (ELOP) are used instead of mechanical oil pumps (MOP) because MOP cannot obtain adequate flow rates during engine shutdown and restart. The twin oil pump system aims to reduce mechanical loss using MOP and ELOP, which are smaller than conventional CVT. The MOP is used to reduce mechanical loss in low-flow situations where the vehicle speed is kept constant. The MOP and ELOP are used in conjunction during heavy braking and rapid acceleration conditions, which require a significant flow rate. In the case of an idle stop or a coast stop, where the engine stops during low-speed driving, the ELOP is operated in place of the MOP [(1)].

To cancel the sailing stop, the accelerator pedal, brake pedal, or shift lever is operated to return to the normal running mode. Here, the reacceleration is of particular importance. The key is approaching the sense of acceleration close to the normal driving mode during accelerator pedal operation when the acceleration demand is high, such as in an overtaking scene on a highway.

The following chapter explains the requirements for the operation's performance.

3. Requirements for operation performance

Drivability performance indicates the smoothness and stability of the drive when the driver accelerates/decelerates the vehicle. During re-acceleration, linear and smooth accelerations are required to respond closely to the accelerator operation. In the case of normal re-acceleration without a sailing stop, a rapid downshift is achieved by the CVT in a coordinated manner with engine control. The lag and response (Fig. 2) were used as performance indicators. The same indicators were used for re-acceleration from the sailing stop. The lag indicates the period between the accelerator pedal depression and the initial response. A long lag leads to response delay and the driver feeling idle. The response indicated the time required to reach an acceleration that matched the accelerator operation. These indicators were defined based on the benchmark results of DCT vehicles while considering marketability.

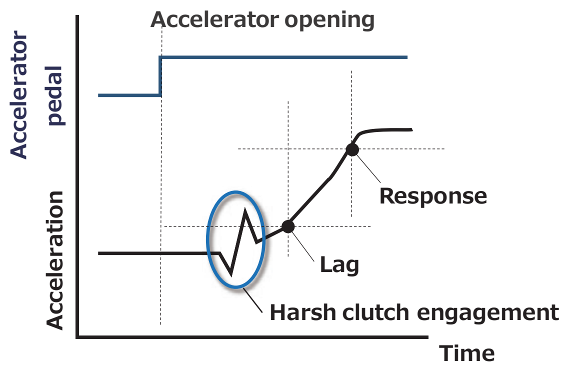

Fig. 2 Acceleration feeling index

Sailing-stop re-acceleration (Fig. 3) requires the operation of phase A before phase B, which usually corresponds to the re-acceleration conditions. In phase A, the clutch is put into the engagement-standby state from the release state and into the engaged state after synchronizing the clutch rotation speed. The sense of linear acceleration can be realized by shortening this synchronization time. For this purpose, it is important to control the following three factors:

- Engine speed
- Rotation synchronization by variator shift
- Timing of clutch engagement

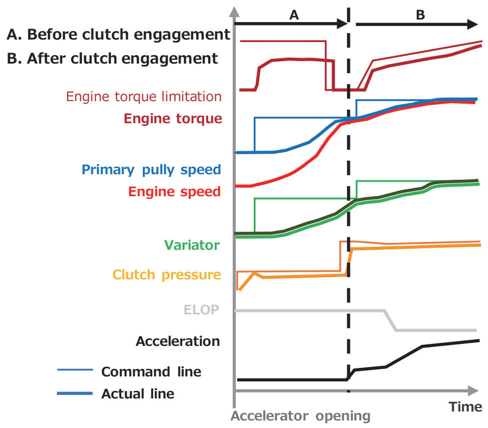

Fig. 3 Re-acceleration control concept

The CVT has the advantage that the flexibility to set the gear ratio is higher than that of the stepped transmission DCT; hence, it is easy to realize stable lag and response by providing accurate amounts of downshift according to the required driving force. However, to obtain smooth acceleration without harsh clutch engagement (Fig. 2), it is necessary to obtain a condition in which the three factors mentioned above are accurately controlled to achieve highly precise coordination (control balance).

4. Measures for smooth re-acceleration

4.1 Strategy for lag and response

While re-accelerating, during which the accelerator pedal is deeply depressed, the demand for lag and response increases. In particular, in the medium to high-speed range where the variator transmission ratio becomes high, the downshift function before clutch engagement shown in Fig. 4 (hereafter referred to as "Pre-low down shift") becomes important. For example, when the clutch is engaged, as described above, the acceleration response worsens with the clutch engagement time compared with normal re-acceleration. To address this problem, a pre-low downshift function is added to guarantee the required driving force after clutch engagement. There is a tradeoff between lag, response, and harsh clutch engagement. When the amount of downshift is too large, the gear ratio becomes low, and the sensitivity to harsh clutch engagement increases, likely to cause rough acceleration. In addition, the shift time is prolonged, and the time to complete the clutch engagement (phase A) is delayed, thereby worsening the lag. However, when the amount of downshift is too small, the worsening of lag can be avoided, but the downshift occurs only after the completion of clutch engagement (phase B), which delays the generation of the driving force up to the target response time. Therefore, the amount of pre-low downshift must be optimized to balance the desired lag and response times and sensitivity to harsh clutch engagement.

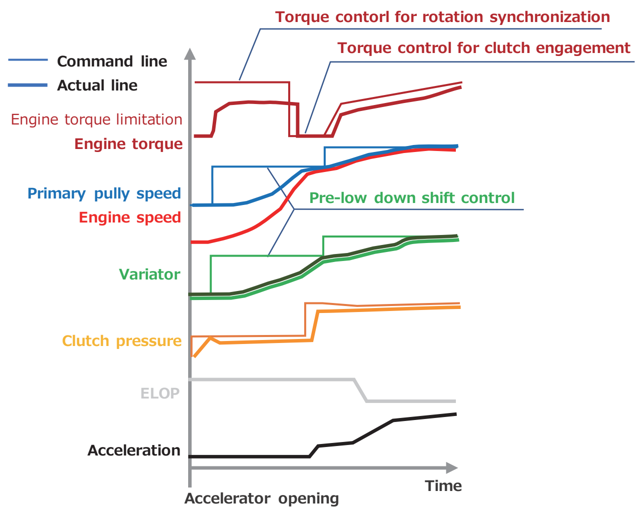

Fig. 4 Method of re-acceleration improvement

4.2 Strategy for harsh clutch engagement

To realize a smooth acceleration performance with suppressed harsh clutch engagement, it is necessary to engage the clutch by controlling the clutch differential rotation below the target differential rotation (Fig. 5). The clutch input speed becomes the turbine shaft speed, which is synchronized with the engine speed by the lockup. The clutch output speed was the primary pulley speed of the variator.

Clutch differential rotation = clutch output speed - clutch input speed (1)

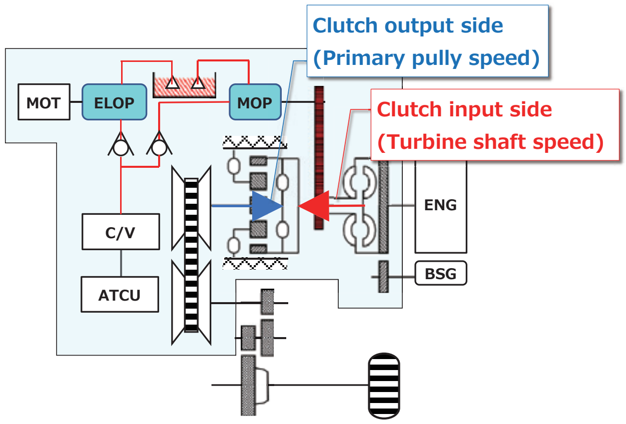

Fig. 5 CVT-X block diagram

The clutch engagement steps until completion are as follows (Fig. 4).

1)Clutch input speed control

After restarting, the rotation-synchronizing torque control increased the engine speed to the target speed.

2)Clutch output speed control

It is increased to the target speed by pre-low downshift.

3)Pre-clutch-engagement input/output shaft control

The input/output shaft is controlled within the target rotation by clutch-engagement torque control.

4)Start of clutch engagement

Clutch engagement is completed within the target differential rotation.

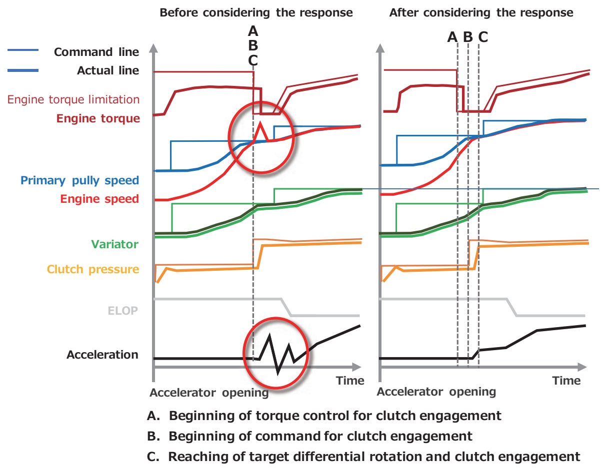

Fig. 6 Clutch engagement harsh optimization

The time required to commence steps 3) and 4) (Fig. 6A, B) was determined using Equations (1) and (2), respectively.

Differential rotation to judge the completion of shift change = target clutch input speed - target variator ratio × secondary pulley speed (2)

The timings of steps 3), torque control, and 4), the start of clutch engagement, must be adapted considering the response delay, which is the time from the command of the control to the actual response. For example, if it is simply set to the target differential rotation without considering the above, harsh clutch engagement push up occurs (Fig. 6, left). After the clutch engagement command is given, the actual engagement is not completed in time; thus, the engine speed through the target, which causes a sudden torque increase owing to the inertial torque upon clutch engagement. Therefore, as shown in Fig. 6 (right), smooth acceleration is realized by adapting the start timing considering the response delay.

4.3 Engine Control Coordination

Furthermore, to suppress harsh clutch engagement, it is necessary to adopt suitable engine characteristics and CVT characteristics. The following two characteristics were particularly influential:

1)Engine re-startability

When the sailing stop is activated, the engine slows down owing to inertia and finally stops completely (hereafter referred to as the engine stops). Depending on the timing of the driver cancel operation, the engine is restarted during the engine stops, and the restarting method is switched between the Belt-driven Starter Generator (BSG) method and the injection method, depending on the number of revolutions at that time. Smooth acceleration was achieved by stabilizing the difference in the rate of increase in the engine speed between the two methods through rotation-synchronizing torque control.

2)Timing of engine restart, variation in the rate of increasing engine speed

Some causes of the variation in the increasing engine speed rate are the piston cycle state at the engine stops and the intake air temperature. For example, when the piston of the engine stops in the compression stroke, restarting is delayed. Because the engine restart control prioritizes avoiding the stalling engine, clutch-synchronizing torque control from the CVT is not accepted, the engine speed increases largely, and harsh clutch engagement occurs (Fig. 7).

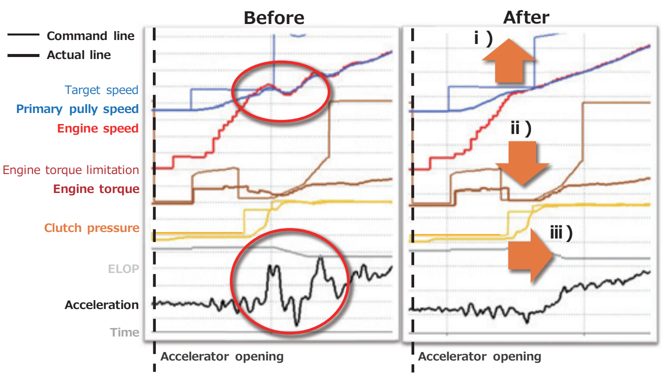

Fig. 7 Engine control interference and the measure

This problem can be avoided by adopting the following measures (Fig. 7):

i)Increasing the amount of pre-low downshift, delaying the start timing of clutch-engagement torque control, and avoiding interference from the restart control.

ii)Limiting the amount of clutch-engagement torque control in proportion to the downshift to the lower side and adjusting the driving force after clutch engagement to balance the harsh clutch engagement.

iii)When the torque limit is tightened, the rotation rate increases slowly. By delaying the time required to start clutch engagement in accordance with the increase in the rotation rate, it is possible to realize smooth acceleration performance while controlling the engine restart timing and rate variation.

As described above, a linear and smooth acceleration, corresponding to the operation of the accelerator by the driver, was realized by adapting the CVT considering the engine characteristics and control (Fig. 8).

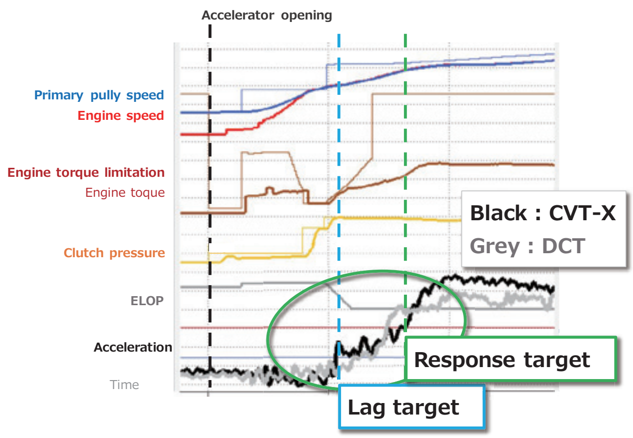

Fig. 8 Comparison CVT-X and DCT

5. Summary

In this development, it was possible to prove the technical value position where stable lag and response performances can be easily realized by step-less transmission, which is an advantage of CVT over the DCT (Fig. 9).

It was possible to suppress the harsh clutch engagement, which the DCT managed by clutch-slip control, to realize a highly competitive linear and smooth acceleration performance by precisely coordinating the control that considers three factors (engine speed, variator shift ratio, and clutch engagement). In this development, the tradeoff between lag, response, and harsh clutch engagement was satisfied by preemptively clarifying the target performance values of each function and the key considerations in rate variation, whereby it was possible to narrow down the key points to be considered. By realizing this function, the attractive quality of the CVT-X was improved.

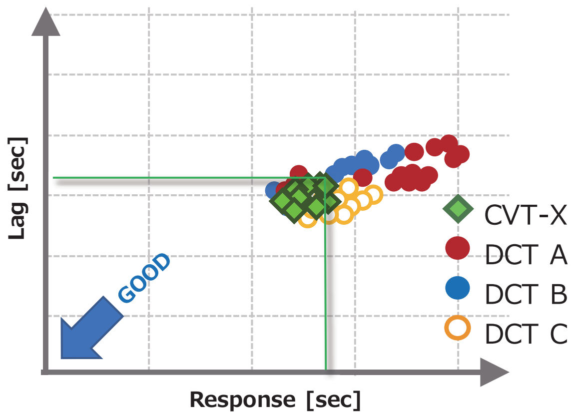

Fig. 9 Re-acceleration performance comparison with competitive DCT cars

6. References

(1)Shingo SUZUKI, Kohei TOYOHARA, Makoto OGURI, Masaya MATSUMURA:Development of a new CVT featuring high efficiency and wide ratio coverage, JATCO Technical Review No.22, p.74 - 79.

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