Variable Valve Actuation Systems for Environmentally Friendly Engines

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OVERVIEW: Use of variable valve actuation in engines has become more common in recent years as an effective technique for improving fuel economy and exhaust emissions as well as engine output, and it is growing in importance as a promising technique for reducing CO_2 in response to environmental problems in particular. Hitachi commercialized VTC in the mid-1980s and commenced mass production of VEL in 2007. VTC is becoming a standard feature in gasoline engines and the fuel economy benefits of VEL when used in combination with VTC have seen it adopted increasingly wider. Hitachi is working on further enhancements to variable valve actuation which has a key role as a technology for complying with fuel economy regulations.

INTRODUCTION

VEHICLE engines have made remarkable progress since they first appeared and the operating range of engines in terms of rpm (revolutions per minute) and torque have expanded significantly. However, optimum engine design becomes difficult if the operation timing of the engine valves is fixed. For this reason, variable valve actuation has been used to optimize the valve timing in response to the operating conditions since the 1980s. Although the technique was initially used in a limited way for applications such as simultaneously achieving both higher output and stable combustion when idling, its effectiveness has grown as fuel economy and exhaust emission regulations have tightened and it has been adopted as a means of complying with these regulations.

Hitachi was ahead of its Japanese competitors in commercializing use of VTC (valve timing control) to

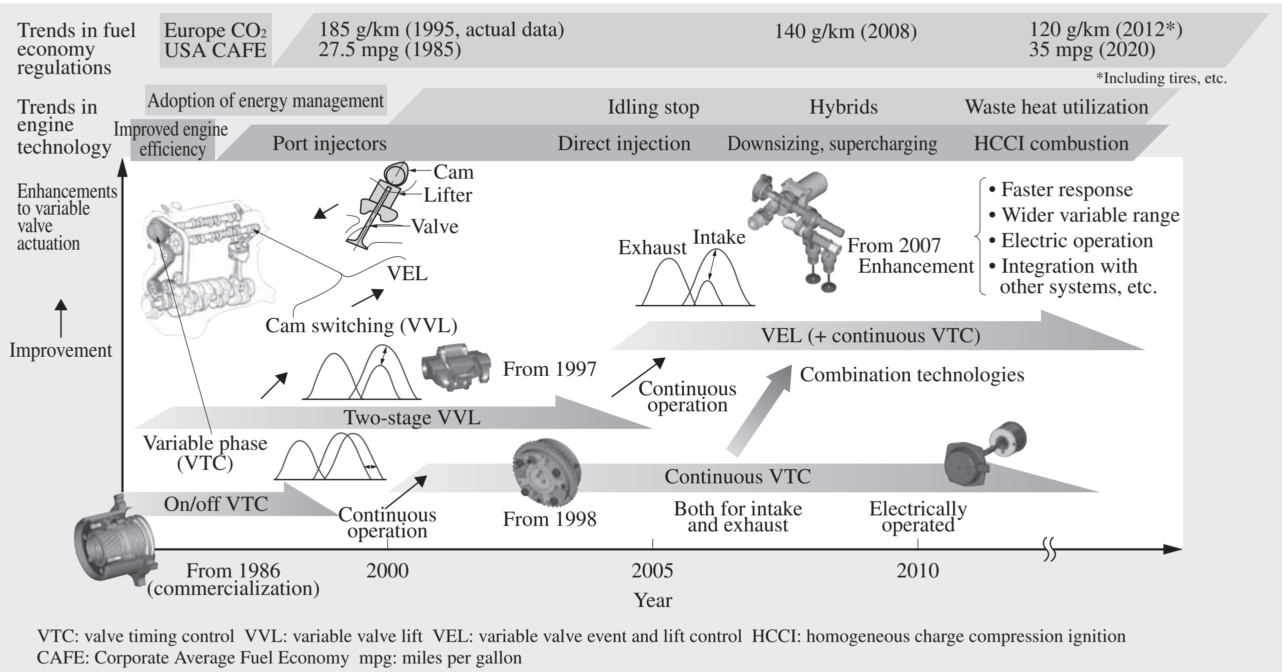


Fig. 1—Enhancements to Variable Valve Actuation.

Variable valve actuation is growing in importance as a technology that benefits both vehicle performance and the environment. The technology will be enhanced further in its role as a key technology for reducing CO_2 (carbon dioxide) emissions from future vehicles.

change the cam phase in the mid-1980s. Hitachi started developing variable lift in the 1990s, first introducing VVL (variable valve lift) and later VEL (variable valve event and lift control) which was selected for the Infinity G37 (V6, 3.7 L) from Nissan Motor Co., Ltd. and other vehicles and entered mass production in 2007 (see Fig. 1).

This article describes the performance benefits of variable valve actuation systems which are an effective means of making engines more environmentally friendly, and gives an overview of VTC and VEL which are typical examples of variable valve actuation systems.

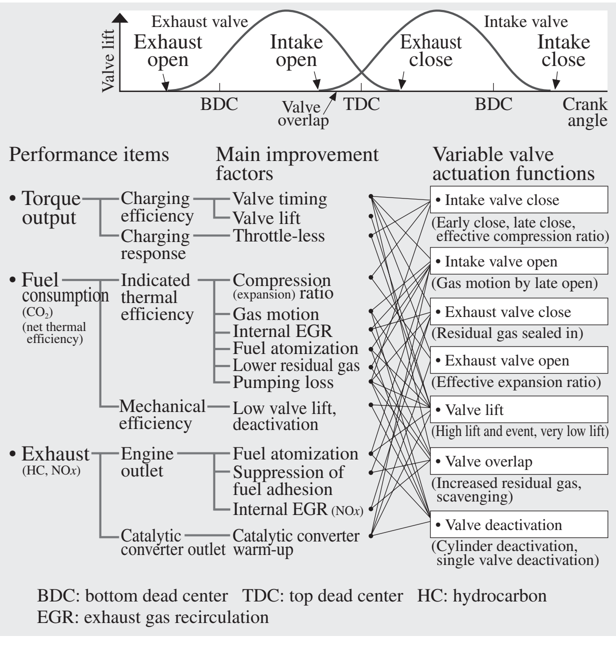
FUNCTIONS AND PERFORMANCE BENEFITS OF VARIABLE VALVE ACTUATION

Traditionally, the requirements for valve actuation mechanisms were higher lift and faster operation. These are also key issues for variable valve actuation where the mechanism is more complex. On top of this, there is a need to use the variable mechanism to improve combustion and obtain better thermal efficiency in order to get better fuel economy and emission performance. Fig. 2 shows the relationship between variable valve actuation functions and the factors that improve engine performance.

The benefits of variable valve actuation are not limited to engine output and include fuel economy and exhaust emissions. In terms of thermal efficiency, variable valve actuation has major benefits that include reducing the pumping loss associated with the timing while the intake valve is closed as well as achieving better combustion by better gas motion and fuel atomization through lower valve lift.

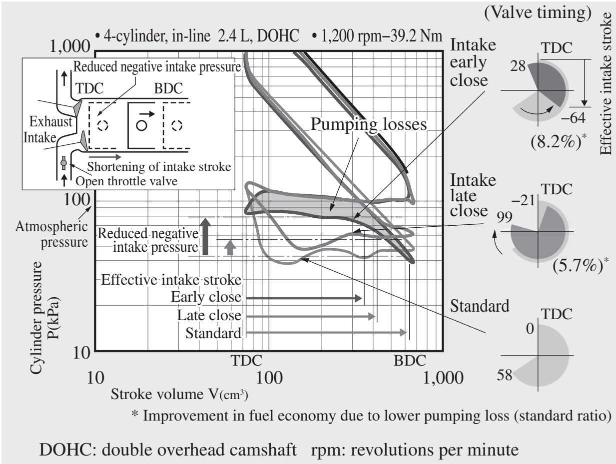
Fig. 3 shows an example of the reduction in pumping loss achieved by variable valve actuation.

Fuel consumption is improved by approximately



BDC: bottom dead center TDC: top dead center HC: hydrocarbon
EGR: exhaust gas recirculation

Fig. 2—Relationships between Engine Performance Improvement Factors and Variable Valve Actuation Functions.
Variable valve actuation has extensive benefits for fuel economy and exhaust emissions as well as engine output.



DOHC: double overhead camshaft rpm: revolutions per minute

Fig. 3—Pressure Change in Cylinder and Reduction in Pumping Loss Achieved by Valve Timing.
By using late close or early close for the intake valve, the effective intake stroke can be shortened and the throttle opened accordingly. This reduces the negative intake pressure and reduces pumping loss.

○: Possible △: Partially possible ×: Not possible

Phase, Lift, Event

	Type	Valve lift characteristics	Phase	Lift	Event	Deactivation	Continuous control	Engine performance	Installation	Cost
With cam	Valve timing control (VTC)		○	×	×	×	○	Low	Good	Low
With cam	Cam switching (VVL)		△→○*	○	○	○	×→△*	↑	↑	↑
With cam	Variable valve event and lift control (VEL)		△→○*	○	○	○	○	↓	↓	↓
Without cam	Hydraulic or electromagnetic drive		○	○	○	○	○	High	Poor	High

* Additional functions made possible by combining with valve timing control.

Fig. 4—Comparison of Types and Functions of Variable Valve Actuation.
Enhancing the functionality improves engine performance but brings significant problems of cost and installation.

8% under partial load. In terms of exhaust emissions, a significant reduction is achieved in the HC (hydrocarbon) and NO*x* (nitrogen oxide) toxic components. With advances in catalytic technology, the level of HC emissions before the catalytic converter warms up when the engine is started from cold remains a current problem but significant benefits can be obtained in this area by using techniques such as low lift for fuel atomization and overlap control to suppress fuel adhesion to walls. Fig. 4 shows the classification of the specific mechanisms used for variable valve actuation.

Although greater functionality leads to better performance, it also brings significant problems such as cost and installation[1].

VTC SYSTEM

As VTC uses the actuator on the sprocket at the end of the camshaft to perform phase conversion as shown in Fig. 5, the system is simple and practical. Hitachi initially produced the system using hydraulic on/off control with a helical gear mechanism. Although the gear noise resulting from the alternating torque on the camshaft is an issue for VTC, this was resolved by a backlash elimination mechanism devised by Hitachi. Subsequently at the end of the 1990s, Hitachi commercialized a vane-type system with fast response and large conversion angle using continuous control. As continuous control optimizes the valve timing based on the operating conditions, it requires a high degree of precision. Specifically, crank angle, cam angle, and other sensor signals drive a solenoid valve that adjusts the oil pressure in the VTC hydraulic chamber. This continuous control mechanism significantly improves fuel economy, emissions, and other parameters and has become a standard feature on gasoline engines. Although the technique is mainly used for the intake valves, use on the exhaust valves is becoming more common. In particular, it is used to reduce turbo lag in direct-injection gasoline engines by improving the scavenging efficiency and other factors using valve overlap in combination with turbocharging. It is anticipated that future needs will include demand for electrically operated systems that can optimize valve timing from the moment the engine is started.

VEL SYSTEM[2], [3]

The concept of using variable lift to change the lift and valve opening duration (events) has been a subject of research since the 1960s. Hitachi's first such product was VVL, but because this involved switching between two settings it was unable to provide sufficient fuel economy benefits and therefore Hitachi went on to develop VEL. The development of VEL drew on Hitachi's experience from prototype development for SOHC (single overhead camshaft) engines in the early 1980s[4].

Basic Design and Principles of Operation

Fig. 6 shows the configuration of a VEL system. The main development objectives were to: (1) ensure that the system could be added to existing engines with minimal modifications, (2) provide a wide range of lift and event variation, (3) allow high engine rpm, (4) low drive friction, and (5) highly responsive control. To

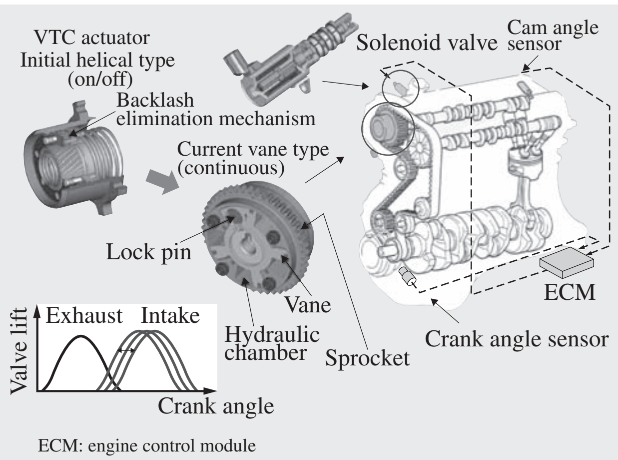


Fig. 5—VTC System.
The hydraulic pressure to the VTC is controlled based on the crank angle, cam angle, and other sensor signals.

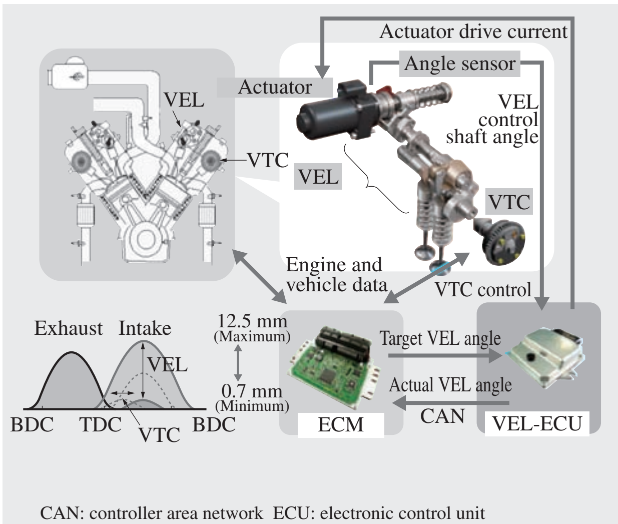


Fig. 6—VEL System.
VEL lift control and VTC phase control operate in tandem.

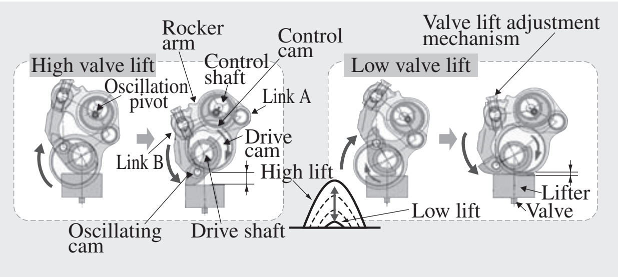
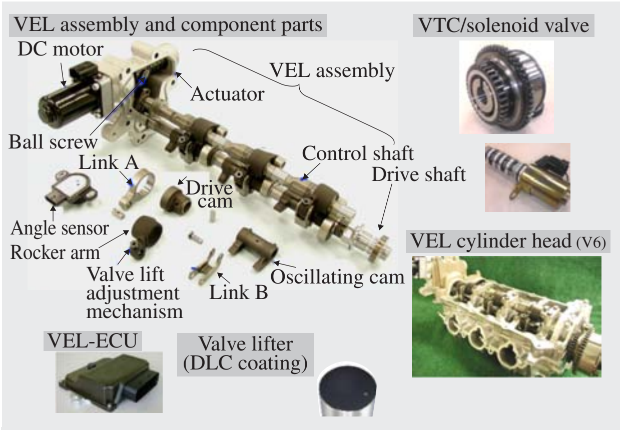


Fig. 7—VEL Principle of Operation.
The oscillation position of the oscillating cam can be modified to change the valve lift.



DC: direct current DLC: diamond-like carbon

Fig. 8—VEL Assembly and Component Parts.
As the drive shaft is located where the conventional camshaft used to be, the VEL assembly is compactly fitted in the cylinder head.

ensure practicality, the variable mechanism was located in the empty space between cylinders without changing the camshaft position in existing engines.

Fig. 7 shows the principle of operation of VEL. The cyclic motion generated by the rotation of the drive cam is transferred to the oscillating cam by the multi-link mechanism. Moving the rocker arm oscillation pivot up or down changes the oscillation position of the oscillating cam and therefore modifies the lift and events in a continuously variable way. A feature of VEL is that it uses the multi-link mechanism to forcibly transfer the cyclic motion to the oscillating cam. This reduces the drive friction in the mechanism because no return spring is required to pull back the oscillating cam. The forced drive via the multi-link mechanism also facilitates higher engine speeds and the system shown can operate at up to 7,500 rpm, the highest rpm achieved by the mechanism of this type. VEL improves fuel economy and engine output because it can control the valve lift over a wide range (0.7 mm to 12.5 mm). In particular, throttle-less operation can be used with very low lift which significantly reduces the pumping

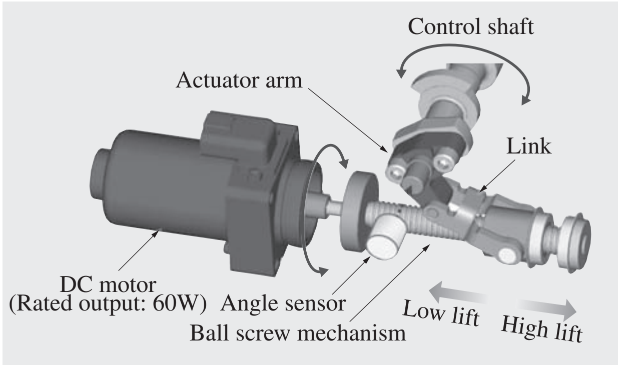


Fig. 9—VEL Actuator.
Features such as the highly efficient ball screw reduction mechanism allow a smaller electric motor to be used.

loss associated with the throttle. Also because the valves are used for throttling, the acceleration response is also improved due to better intake charge response. Although cylinder to cylinder variation in intake was an issue when using very low lift, this was resolved using a unique lift adjustment mechanism.

Fig. 8 shows the VEL assembly and component parts and Fig. 9 shows the VEL actuator. The actuator consists of a brushed DC (direct current) motor, ball screw reduction mechanism, and control shaft angle sensor. Features such as the low friction of the VEL mechanism and high transmission efficiency of the ball screw mean highly responsive control can be achieved using a small electric motor with a rated output of 60 W.

Control System

VEL drive control is performed by using the vehicle and engine data to calculate the target values for VEL in the ECM (engine control module) and then sending these to the VEL-ECU (VEL electronic control unit) via the CAN (controller area network) (see Fig. 6). The VEL-ECU then performs actuator drive control using the angle sensor signal from the control shaft as feedback.

In addition to a high level of responsiveness and stability, the functions required for VEL drive control include: (1) ability to specify the frequency response characteristics, (2) a high degree of robustness over time and with respect to changes in ambient conditions, and (3) low electric power consumption of the electric motor. Model reference control with two degrees of freedom was adopted to achieve (1) and (2). For (3), a specially designed model reference filter circuit was used. VEL generates an alternating torque in the control shaft from the reaction force of the valve

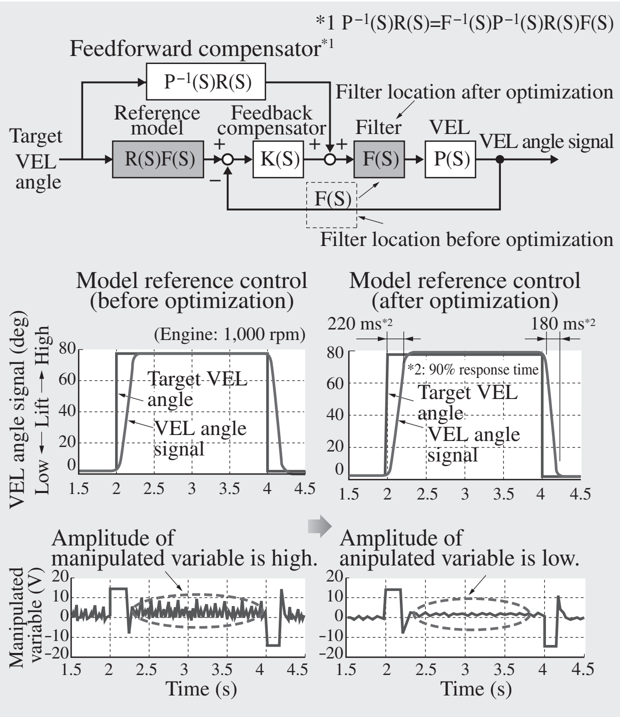


Fig. 10—Block Diagram of VEL Drive Control and Optimization of Filter Location.
The transfer characteristics were optimized by placing a filter in the output stage of the drive control to prevent the value of the manipulated variable from getting too large.

springs and other sources. This alternating torque can interfere with the actuators and, if the value of the manipulated variable used to suppress this torque becomes large, the result is an increase in the power consumed by the electric motor. Although filtering the sensor signals is one way to prevent this increase in the value of the manipulated variable, this leads to a loss in responsiveness. To resolve this problem, a filter was placed in the drive control output stage as shown in Fig. 10 and the control system was redesigned to include a reference model by assuming the transfer characteristics obtained when this filter is treated as part of the frequency characteristics of the VEL mechanism. The resulting control system successfully suppresses the amplitude of the manipulated variable without loss of responsiveness or stability. The electric power consumption of the VEL system in actual use is 2.2 W which is less than the power used by the VTC solenoid (2.8 W).

Thanks to the above mechanisms and control developments, the performance benefits provided by VEL when deployed in an actual vehicle include fuel (CO_2: carbon dioxide) savings of approximately 10%, a reduction of approximately 50% in exhaust (HC) emissions when cold starting, and an increase of approximately 10% in engine output.

Future issues for VEL include further improving responsiveness, expanding the variable range, reducing costs, and making the mechanism more compact.

CONCLUSIONS

This article has described the performance benefits of variable valve actuation systems which are an effective means of making engines more environmentally friendly, and given an overview of VTC and VEL which are typical examples of variable valve actuation systems.

The more sophisticated variable valve actuation systems become, the greater the number of control parameters involved and the more advanced the system development capabilities that are needed. With VEL, an optimum system was able to be commercialized by developing the mechanism and control systems in tandem. Although there is an ongoing shift to electrically driven power trains in response to strict environmental regulation, it is likely that the internal combustion engine will remain the mainstay for the time being and it is anticipated that variable valve actuation will have an increasingly important role in extracting the maximum efficiency from these engines.

Hitachi intends to utilize its system development capabilities and various underlying technologies to enhance the functions of variable valve actuation as far as possible at a reasonable cost. Hitachi's strategy is to help reduce CO_2 emissions from vehicle engines by pursuing a combination of technologies that includes direct injection, turbocharging, HCCI (homogeneous charge compression ignition) combustion, and hybrid systems.

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