

Numerical Analysis of Turbocharger Response Delay Mechanism

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ABSTRACT

Social demands for increased automotive fuel efficiency are today increasing. Turbocharged downsized engines have attracted attention as one technological means of responding to these demands. Boosting technology using a turbocharger is effective in increasing fuel efficiency, but these turbochargers also display a response delay characteristic known as turbo lag, which may cause engine performance to decline. This issue impedes the broader application of this technology. The research discussed in this paper focused on turbo lag, and adopted a numerical approach to analyzing the detailed mechanism of this phenomenon. The study concluded that turbo lag is a delay in the boost pressure response that originates from a combination of factors. The primary factor in turbo lag is a delay that is due to a physical property of the turbocharger system; the secondary factor is a decreased turbine effective energy caused by a shift of operating point, resulting from the primary factors.

1. Introduction

The demands of society for the achievement of increased automotive fuel efficiency are increasing today, against the background of the need to reduce CO₂ emissions in order to address the issue of global warming and the spiraling cost of oil. In addition, the trend towards the establishment on the national level of fuel efficiency-related laws and regulations aiming towards the reduction of CO₂ emissions – including the 2015 Japanese fuel economy standards, European regulations on CO₂ emissions, and the U.S. new CAFE regulations – is expanding rapidly⁽¹⁾⁻⁽³⁾. Given this, the realization of increased fuel efficiency is, together with the achievement of cleaner exhaust emissions, a social responsibility for automakers.

Among available methods of increasing fuel efficiency, engine hybridization and turbocharging and downsizing are presently attracting a great deal of attention. While the rate of improvement of fuel efficiency achieved using turbocharging and downsizing is lower than that achieved by hybridization, the technology is lightweight, compact, and comparatively low-cost. For these reasons, automakers are focusing considerable attention on turbocharging and downsizing as a technology to increase the fuel efficiency of their vehicle line-ups, and its application is projected

to increase in the mid- to long-term⁽⁴⁾.

Among turbocharged downsized engines, turbocharging is a technology that is applied to increase fuel efficiency and displays a high level of system efficiency because it enables exhaust energy to be regenerated and reused. However, boosting using a turbocharger is also known to induce a decline in engine performance across a wide driving range due to a response delay characteristic known as turbo lag. In particular, turbochargers display insufficient responsiveness at low engine speeds, when exhaust energy is relatively low. The delay in response in this driving range, which is used frequently in actual driving, is a factor in performance decline in terms of drivability, fuel efficiency, and emissions. The enhancement of turbocharger response will be a key factor in enabling turbocharged downsized engines to be used in future as substitutes for natural aspiration engines (“NA engines” below), and to play a central role in the achievement of a new era of fuel efficiency.

Numerous attempts have been made to date to enhance turbocharger response, and papers have been published discussing a variety of methods of doing so⁽⁵⁾⁻⁽⁸⁾. However, few of these have focused centrally on the mechanism of turbo lag. This is due to the fact that turbochargers contain a large number of non-linear

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elements, and operate recurrently, making it challenging to analyze the phenomenon in an actual turbocharger unit. The research discussed in this paper constructed a physical model of a turbocharger and adopted a numerical approach to the analysis of the detailed behavior of the turbocharger under transient operating conditions and the mechanism of turbo lag.

2. Effect of Turbocharger Response Delay on Turbocharged Downsized Engines

2.1. Fuel Efficiency Increases in Turbocharged Downsized Engines and Current Trends

In order to illustrate the effect of turbocharging and downsizing on fuel efficiency, representative turbocharged downsized engines and NA engines, currently available on the market, were selected and their displacement against rated power (Fig. 1) and fuel efficiency in NEDC mode⁽⁹⁾ (Fig. 2) were compared. With regard to engine displacement, turbocharged engines achieve an identical rated power to NA engines at a lower displacement. For example, while a displacement of approximately 2.8 L is necessary for a NA engine to achieve a rated power of 150 kW, the turbocharged engine is able to achieve the same rated power at a displacement of approximately 2.0

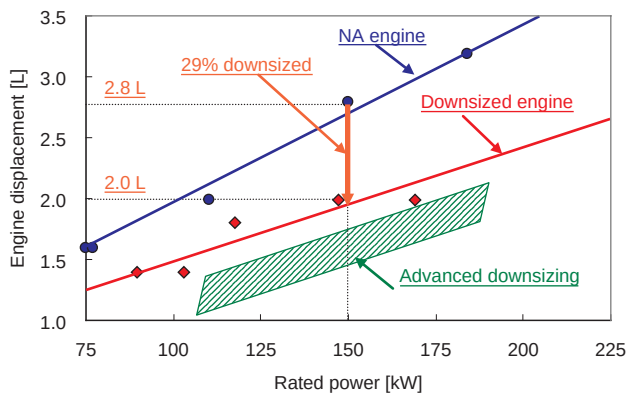


Fig. 1 Comparison of engine displacement

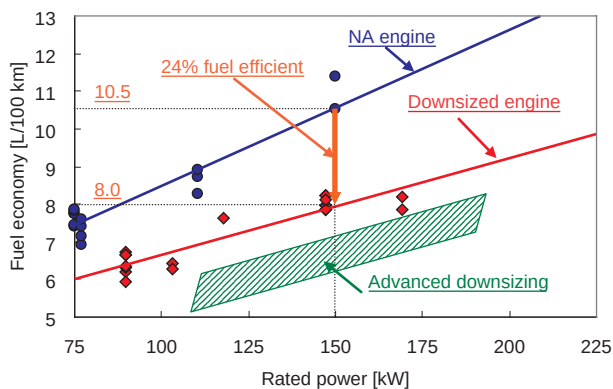


Fig. 2 Comparison of fuel consumption rate of turbocharged engine and NA engine

L, approximately 29% lower. Comparing fuel efficiency at the same rated power of 150 kW, the vehicle using a turbocharged downsized engine displays an approximately 24% higher level of fuel efficiency than the vehicle using a NA engine. This result originates in the fact that turbocharging increases power density, enabling a lower-displacement engine than a NA engine to be used, thus reducing mechanical loss and pumping loss. Given this, it can be conjectured that the effect of turbocharging and downsizing in increasing fuel efficiency is dependent on the rate of reduction of displacement (the rate of downsizing). Figure 1 shows that the rate of downsizing in turbocharged engines currently available on the market is basically 25-30%. However, downsizing to a rate of around 50% has recently been proposed as a method of achieving further gains in fuel efficiency, and there is a trend towards the development of engines in which a higher rate of downsizing is enabled by the achievement of increased boost pressure and increased power density⁽¹⁰⁾.

2.2. Limitation on Rate of Downsizing due to Turbocharger Responsiveness

Increasing the rate of downsizing by achieving increased boost pressure and power density is the key to the achievement of further increases in fuel efficiency, and this is becoming a trend in engine development. The power density of turbocharged engines can be increased relatively easily by altering the set boost pressure. The achievement of increased power density therefore does not present any major issues. However, when the transient response of a turbocharged engine is considered, issues of drivability limit the achievement of an increased rate of downsizing by increasing boost pressure. Figure 3 shows a contour diagram of boost pressure response time in an in-line 4-cylinder engine fitted with a single variable-vane turbocharger. This contour diagram shows the time taken for the boost pressure to reach the set level when the load is changed in one step from no load to full load for each

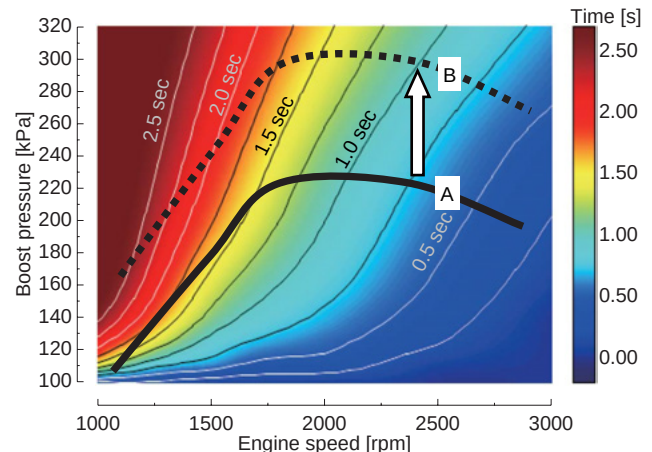


Fig. 3 Boost response time

engine speed. These results show that the lower the engine speed, the slower the boost pressure response. For example, at an engine speed of 1500 rpm, the time taken to reach the target boost pressure (curve A), going from no load to full load, is approximately 1.5 sec. When the target boost pressure is increased to the pressure shown by curve B, assuming that the rate of downsizing was increased by around 30%, it will take approximately 2 sec to reach the target boost pressure at the same engine speed of 1500 rpm, representing a decline of approximately 33% in boost pressure response. The enhancement of turbocharger responsiveness is therefore a major issue in terms of achieving a higher rate of downsizing by means of increasing boost pressure.

3. Numerical Modeling of Turbochargers

3.1. Necessity of Numerical Modeling

The system formed by an engine using a turbocharger is generally formed recurrently from the engine, turbine, and compressor, via mechanical or fluid energy, and when the engine is in operation, the system operates while maintaining a balance of energy between its various elements. Analyses of actual turbocharger units are limited to the measurement of only particular physical quantities, and while these analyses are able to evaluate representative physical quantities such as response delay time, it is challenging for them to obtain a grasp of the behavior of the system in terms of the energy exchange, mutual interaction, and other relationships between the various recurrent influencing factors. The use of numerical models is an effective method of analyzing these relationships and elucidating the detailed mechanism of turbocharger response delay.

3.2. Overview of Numerical Model of Turbocharger

Figure 4 shows a schematic diagram of the constituents of the system formed by an engine-

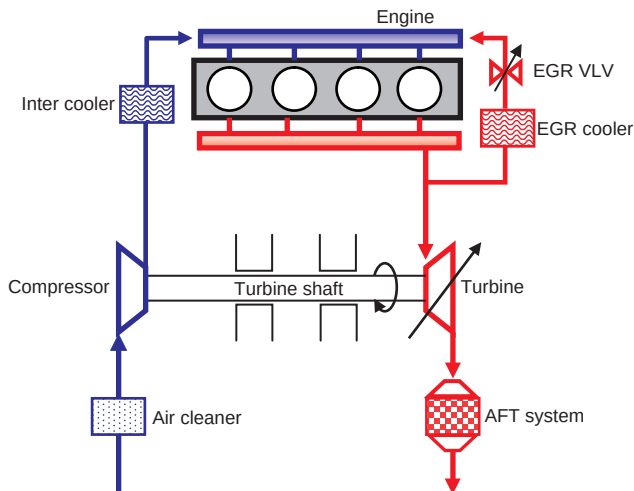


Fig. 4 Schematic diagram of turbocharger system

turbocharger combination. Broadly speaking, the system is made up of three main elements, a compressor, an engine, and a turbine, and the parts that connect these elements, pipes, an air cleaner, an inter-cooler, an EGR valve, and an after-treatment system. In order to create a numerical model of the system, a physical model of turbocharger expressed by Eqs. (1)-(3) was created, and the intake and exhaust elements were modeled using the flow coefficient, as shown by Eq. (4). The model was created with consideration of satisfying the principles of conservation of energy and conservation of mass between the elements of the system.

Below, the main issue of this section, the numerical treatment of the turbocharger, will be discussed. The governing equation of the system is expressed as Eq. (1).

$$\frac{dN_{TC}}{dt} = \frac{60}{2\pi I_{TC} N_{TC}} (P_T - P_C - P_f) \quad (1)$$

The effective turbine work, P_t , and the compressor compression work, P_c , are determined from Eqs. (2) and (3) respectively, using the flow rate, pressure ratio characteristic, and efficiency characteristic as determined from the inlet and outlet boundary conditions and the results of steady-state unit tests.

$$P_T = m_T \eta_T c_p T_3 \left(1 - \pi_t^{\frac{1-\gamma}{\gamma}} \right) \quad (2)$$

$$P_C = \frac{1}{\eta_c} m_c c_p T_1 \left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \quad (3)$$

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \quad (4)$$

Due to the limitations of measurement devices, the turbine and compressor flow characteristics obtained from steady-state unit tests generally do not cover the range of conditions needed for transient analysis. In this project, a unique linearized algorithm was therefore used in order to parameterize these characteristics.

MATLAB Simulink, produced by the Math Works, Inc., was used as the platform for the numerical model (Fig. 5), and the composition of the turbocharged engine system shown in Fig. 4 was reflected in it.

3.3. Verification of Numerical Model

In order to verify the numerical model, a numerical model of an in-line 4-cylinder 2.2 L engine with a single variable-vane turbocharger was formulated, and the behavior of the turbocharger as predicted by the model was compared with the behavior of a turbocharger in an actual vehicle.

Figures 6 and 7 respectively show comparisons of measured and predicted boost pressure and turbocharger shaft speed during operation at FTP75⁽¹¹⁾. In both cases, the values predicted by the numerical model reproduce the actually measured values with a comparatively high degree of accuracy. In addition, Fig. 6 shows that a delay in reaching target boost pressure occurs in the actual vehicle, and the boost pressure as estimated by the numerical model reproduces this phenomenon well. The model was therefore employed in this project to analyze the mechanism of delay in boost pressure response.

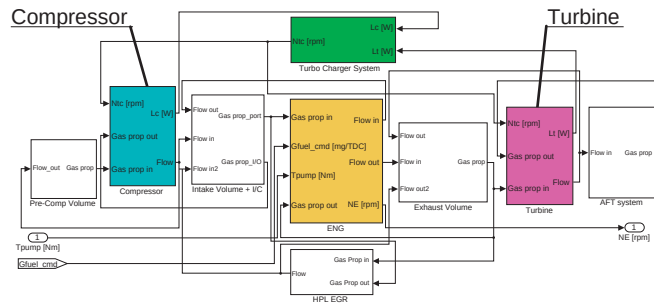


Fig. 5 Schematic diagram of Simulink model

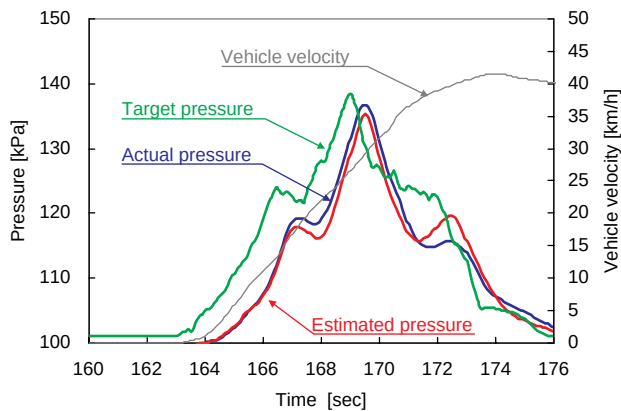


Fig. 6 Comparison of actual and estimated intake manifold pressure at FTP75

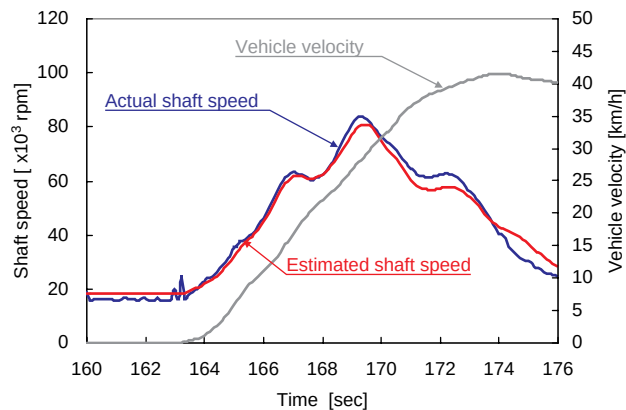


Fig. 7 Comparison of actual and estimated turbine shaft speed at FTP75

4. Analysis of Mechanism of Turbo Lag Using Numerical Model

This chapter will discuss the analysis of the mechanism of the delay in boost pressure response during operation under transient conditions (turbo lag) using the numerical turbocharger model. The analysis employed the numerical model of a diesel engine with a single variable-vane turbocharger that had been proven accurate, and analyzed the low engine speed range that has a particularly significant effect on the transient response of turbochargers.

4.1. Results of Estimation of Delay in Turbocharger Response

Figures 8 and 9 respectively show the change over time in boost pressure and turbocharger shaft speed when the degree of accelerator opening is increased in one step from 10% to 80% at an engine speed of 1750 rpm. As Fig. 8 shows, the target boost pressure increases in one step with the increase in the degree of accelerator opening, but the actual boost pressure does not trace this change, reaching the target boost pressure with a 1.37 sec delay. The turbocharger shaft speed also transitions towards its steady-state value with a 1.37 sec delay.

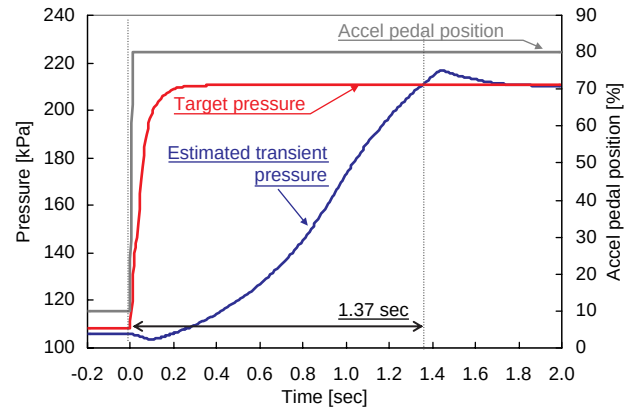


Fig. 8 Estimated intake manifold pressure response under step load condition at 1750 rpm

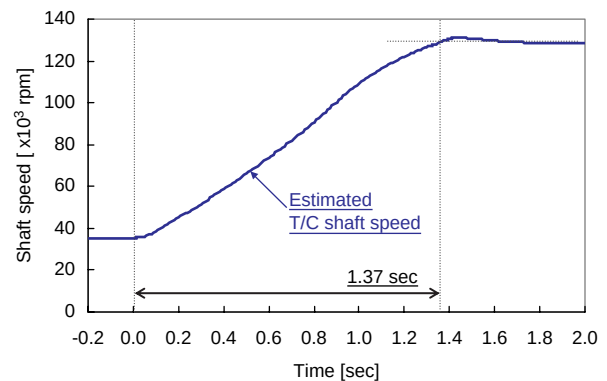


Fig. 9 Estimated shaft speed response under step load condition at 1750 rpm

4.2. Energy Balance during Transient Operation

Because turbochargers are a type of energy converter, converting exhaust energy into intake compression energy, the study of the energy balance in each part of the system is useful in the analysis of turbo lag behavior. Figure 10 shows the work and the different types of loss in each part of the turbocharger system during transient operation under the conditions discussed in the previous section, as estimated using the numerical model.

Figure 10 shows that, due to a variety of factors, the level of effective turbocharger work is reduced under transient operating conditions in comparison to steady-state operation. Considering the results at the point 0.6 sec following the change in the accelerator pedal position, virtually the median point in the time for transition from transient to steady-state operation, there is a decline of approximately 91% in effective turbocharger work under transient operation in comparison to steady-state operation. The two types of transient loss – shaft inertia loss and intake volume loss – which are generally considered as factors in turbocharger response delay, respectively account for declines of 14.3% and 12.3% in effective work. Given this, these two types of loss alone could not fully explain the decline in effective work in the turbocharger. The most significant contribution to the decline in effective work under transient operating conditions was the decline in effective turbine work, which generated a decline of approximately 64.4% in effective work. This made it clear that the behavior of the turbine under transient operating conditions has a significant effect on the transient boost pressure response.

4.3. Mechanism of Decline in Effective Turbine Work

Six factors in the decline in effective turbine work were determined through the use of Eq. (2), the effective turbine work equation derived from thermodynamic relationships. Two of these factors, specific heat under constant pressure and the specific heat ratio, did not change significantly in the projected temperature range, narrowing the factors to be considered in relation to the

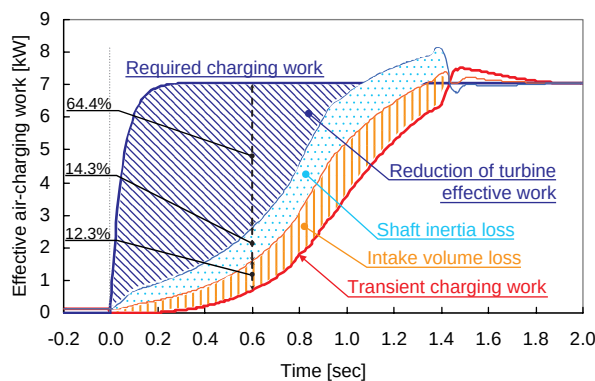


Fig. 10 Analysis of energy distribution in turbocharger system

Table 1 Variation of turbine work-related parameters under transient condition

		Steady state	Transient	Variation [%]
Mass flow rate	[kg/s]	0.0992	0.059	-41
Turbine efficiency	[%]	70.0	42.1	-39.9
Expansion ratio	[-]	1.98	2.04	+3
Inlet gas temperature	[K]	899	981	+9

decline in effective turbine work during transient operation to four: the mass flow rate of turbine working gas, turbine efficiency, the turbine expansion ratio, and the inlet gas temperature. The mechanism of the decline in effective turbine work was sought by comparing the ways in which these four physical quantities changed at 0.6 sec following the change in the position of the accelerator pedal.

As Table 1 shows, the mass flow rate of turbine working gas and turbine efficiency display a significant decline under transient operating conditions as compared to steady-state operation.

Focusing on the mass flow rate first, the table shows that during transient operation the flow rate falls by 41% compared to steady-state operation. While it is easy to speculate that the decline in the mass flow rate of turbine working gas, i.e., a decline in the volume of engine intake, originates in a decline in engine charging efficiency due to the delay in boost pressure response, a reconsideration of the factors in the decline in boost pressure response leads back full circle to the decline in the mass flow rate of turbine working gas. As Fig. 11 shows, this phenomenon originates in the recurrent circulation of energy among the turbine operating gas supply (the engine), the exhaust energy recovery device (the turbine), and the intake air compression device (the compressor). In this type of system, the effects of a decline in one section of the energy flow will propagate recurrently, resulting in a decline in the level of energy flowing in the entire system.

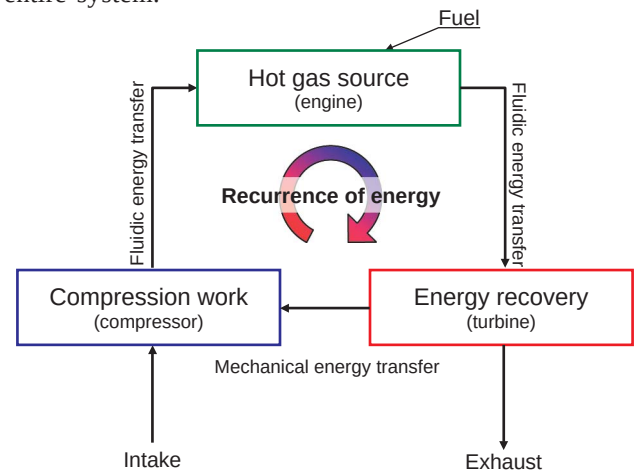


Fig. 11 Schematic diagram of recurrent energy flow in turbocharger system

The decline in turbine efficiency during transient operation will be considered next. A 39.9% decline in turbine efficiency against steady-state operation is observable at the 0.6 sec mark. An analysis of the transition in turbine efficiency over time shown in Fig. 12 indicates that turbine efficiency declines rapidly at the commencement of acceleration, and the efficiency level recovers as the system approaches steady-state operation.

In order to analyze this phenomenon, it is necessary to consider the hydrodynamic properties of the turbine. As Fig. 13 shows, results for turbine efficiency at corrected

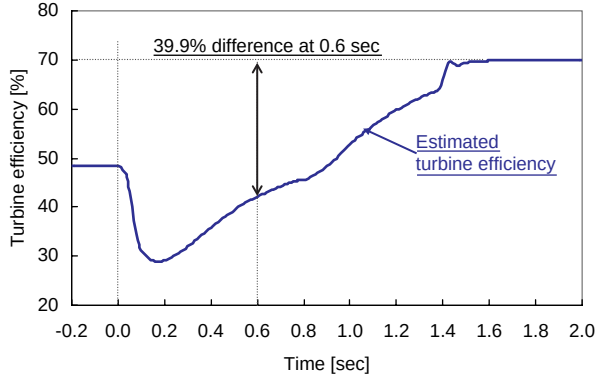


Fig. 12 Behavior of turbine efficiency under transient condition

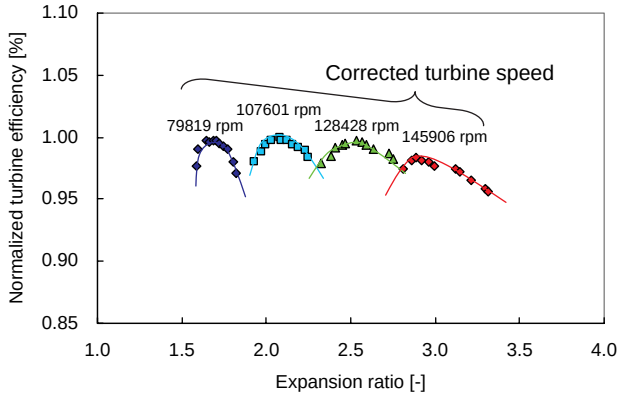


Fig. 13 Expansion ratio-dependency of turbine efficiency

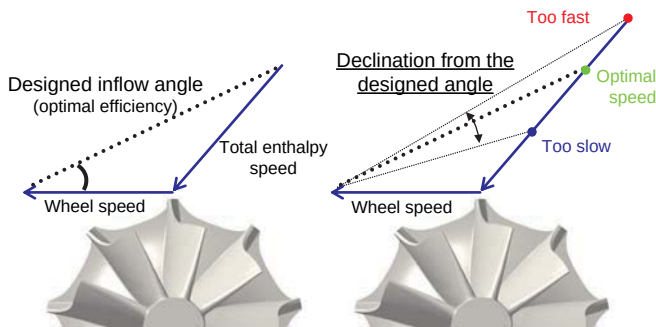


Fig. 14 Relationship between turbine efficiency and speed triangle

turbine speeds display a tendency to group into mountain-shaped patterns in relation to the turbine expansion ratio. As shown in Fig. 14, because of the geometric shape of the turbine, there is an optimum inflow angle for working gas in relation to the turbine blades (the design inflow angle), and if the total enthalpy speed, C in Eq.(5), which expresses the equivalent inflow speed of the working gas, is either too fast or too slow in relation to the peripheral speed of the turbine blades, turbine efficiency will decline.

$$C = \sqrt{2c_p T_3 \left(1 - \pi_t^{\frac{1-\gamma}{\gamma}} \right)} \quad (5)$$

The figure obtained by dividing the peripheral speed of the turbine by the total enthalpy speed of the inflowing gas is generally known as the blade speed ratio (BSR)⁽¹²⁾. As Fig. 15 shows, the BSR can be used to normalize turbine efficiency in relation to turbine speed. A consideration of the transition in the BSR over time under transient operating conditions (Fig. 16) shows that the BSR reaches its minimum value at the commencement of acceleration, and approaches 1 as operation converges on steady-state.

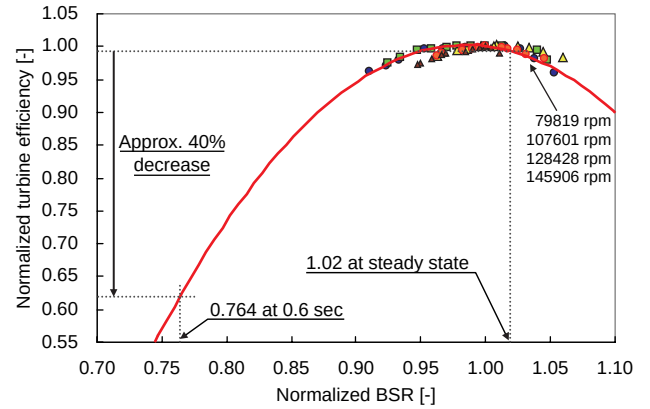


Fig. 15 Normalization of turbine efficiency in relation to turbine speed

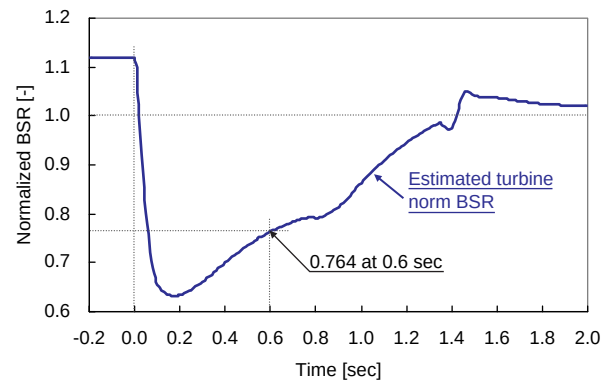


Fig. 16 Behavior of turbine BSR under transient condition

Because the variable vane mechanism generates a comparatively rapid increase in exhaust pressure when the engine operating load increases, the total enthalpy speed of the turbine working gas increases rapidly, but because the peripheral speed of the turbine blades increases more gradually due to the effect of the inertia of the turbine shaft (Fig. 9), the total enthalpy speed transiently exceeds the peripheral speed of the turbine. This means that under transient operating conditions, the BSR declines, and the turbine operates in a range of low efficiency. Figure 16 shows that the BSR of the turbine at 0.6 sec following the change in the position of the accelerator pedal is 0.764. Figure 15 indicates that at this BSR, turbine efficiency declines by approximately 40%. This figure matches the decline in turbine efficiency under transient operating conditions, indicating that the phenomenon can be explained by a change in an operating point (the BSR) of the turbine.

5. Mutual Interaction of Factors in Turbocharger Response Delay

As discussed above, in a standard engine-turbocharger combination, the engine, turbine, and compressor are recurrently connected by mechanical or fluid energy, and the turbocharger operates at the point of energy balance in this recurrence model. Up to this point, three factors in turbocharger delay response have been considered: transient loss, decline in the mass flow rate of turbine working gas, and decline in turbine efficiency. These factors do not only individually affect the turbocharger response, but also produce mutual effects on each other. It is therefore important to elucidate the mutual relationships between these factors in order to fully understand the phenomenon of turbo lag. This chapter will offer an example of the mutual interaction between factors in response delay, and create a model of these factors and the causal relationships between them.

5.1. Reduction in Mass Flow Rate of Turbine Working Gas Induced by Decline in Turbine Efficiency

First, the phenomenon of the delay in the increase in boost pressure due to the decline in turbine efficiency will be considered. As Fig. 17 shows, under transient

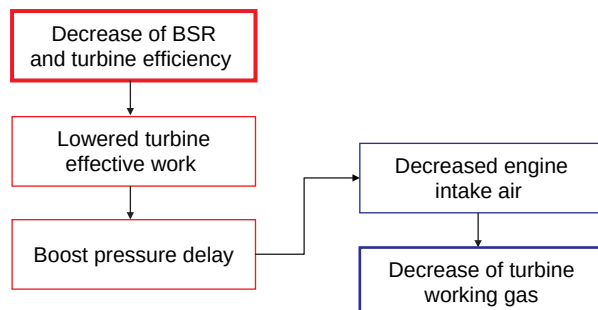


Fig. 17 Propagation of delay factors

operating conditions, due to a rapid increase in exhaust pressure, the turbine BSR decreases and turbine efficiency and the energy recovered by the turbine decline, with the ultimate result that the increase in boost pressure is delayed. This delay in the increase in boost pressure is related to a decline in the volume of engine intake air and the mass flow rate of turbine working gas. In other words, the decline in turbine efficiency induces a decline in the mass flow rate of turbine working gas, another factor in the delay in turbocharger response.

5.2. Model of Factors in Boost Pressure Response Delay and Relationships between Factors

This section will discuss the factors in turbocharger response delay determined up to this point and the causal relationship between these factors, using a multiple recurrence model that contains two coupled recurrence models.

The multiple recurrence model of turbocharger response delay is shown in Fig. 18. This model is made up of a transient loss model, representing the origin of turbocharger response delay, and two recurrence models, a model of the decline in the mass flow rate of turbine working gas and a model of the decline in turbine efficiency. The physical phenomena occurring in the turbocharger that are related to the delay in turbocharger response, and the causal relationships between these phenomena, are connected in Fig. 18 by arrows.

This section will provide a step-by-step explanation of the model, assuming a transition in the engine operating conditions from steady-state to high-load, and a transition from the occurrence of a turbocharger response delay to a state in which the delay no longer occurs.

First, no delay in boost pressure response occurs in steady-state operation. When there is a transition from this state to a state of acceleration, first the transient losses, shaft inertia loss and intake volume loss, occur (A in Fig. 18). As a result, there is a delay in the increase in turbocharger shaft speed, and the turbine efficiency declines due to the hydrodynamic properties of the turbine

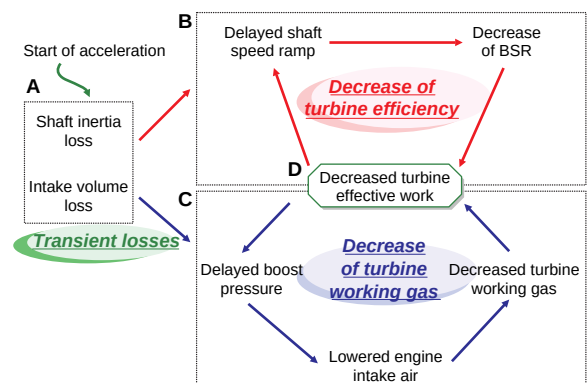


Fig. 18 Multiple recurrence model of turbocharger delay mechanism

(B in Fig. 18). At the same time, the intake volume loss results in a delay in the increase in boost pressure, as a result of which the mass flow rate of turbine working gas declines (C in Fig. 18). As the model shows, these factors in turbocharger response delay act recurrently on each other. Because the respective effects of B and C result in a decline in the effective turbine work (D in Fig. 18), these two factors in response delay can be seen to be connected from the perspective of energy by the decline in the effective work of the turbine.

Because the values of shaft speed and boost pressure depart significantly from their steady-state values at the commencement of acceleration, each of the factors in response delay exerts a mutual effect on each other and the energy flowing through the system as a whole declines. Because of this, there is a significant delay in boost response, but as time elapses, the values of the integral elements, the shaft speed and the boost pressure, increase and ultimately converge on their steady-state values. The factors in response delay that originated with these causal factors - the decline in the mass flow rate of turbine working gas and the decline in turbine efficiency – cease to occur, and the turbocharger therefore arrives at steady-state operation.

As the discussion above indicates, physical factors, the degree of inertia of the shaft and the capacity of the intake system, are the primary factors in the delay in turbocharger response, while a shift in the turbocharger operating point originating in these primary factors results in a decline in turbine efficiency and the mass flow rate of turbine working gas, which become secondary factors in response delay. In addition, these two secondary factors have a mutual effect on each other through the decline in the energy recovered by the turbine.

6. Conclusion

The research discussed in this paper created a numerical model of a turbocharger in order to analyze the mechanism of the delay in boost response occurring in turbochargers. It was verified that the numerical model reproduced the boost response characteristic in an actual vehicle well.

The numerical model was used in the analysis of the mechanism of delay in boost response, with the following results:

- (1) The delay in boost response occurs as a result of three main factors: transient loss, a decline in the mass flow rate of turbine working gas, and a decline in turbine efficiency.
- (2) The decline in the mass flow rate of turbine working gas and the decline in turbine efficiency display recurrent behavior.
- (3) The three factors in the boost response delay are linked by energy flows, and mutually affect each other.

Based on the results of the numerical analysis, it was

concluded that turbo lag is a delay in boost pressure response originating in multiple factors, made up of a delay resulting from primary factors – the shaft inertia loss and intake volume loss collectively termed transient losses – and a delay resulting from secondary factors – a decline in the mass flow rate of turbine working gas and a decline in turbine efficiency.

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