Measurement of Transfer Time Constant of Effective Torque in Internal Combustion Engines*

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So far the studies on the dynamic characteristic of internal combustion engines have been mainly carried out on the governor system and have led to development of a mathematical model more efficient for simulation and control purpose. But, there are still uncertain dynamic behaviors of the engine. The experiment and analysis on the transfer characteristic of effective torque under a changing fuel feed quantity or brake load were carried out by using the frequency response and indicial response methods. Consequently, it was confirmed that the transfer response of effective torque to the changes in fuel feed quantity and brake load comprises a response time lag and its time constant is variable with the operating condition of the engine.

Key Words: Internal Combustion Engine, Effective Torque, Transfer Time Constant, Engine Speed Response, Transient Operation.

1. Introduction

There are various running modes of an internal combustion engine and a considerable percentage of them are occupied by transient operations in which the engine speed and brake load fluctuate. Even in such transient running as above, it is desirable to improve the output performance and exhaust gas composition, to reduce the engine noise, to make the speed response better, etc. The transient characteristics of an internal combustion engine have been so far studied mainly by a method of analysing, linearly as well as nonlinearly, the dynamic stability of a closed loop including the governor system^{(1)~(3)}.

The speed of engine is originally governed on the basis of an interaction between its governing system and the engine. For this reason, a more strict analysis can be only realized by means of utilising the detailed data obtained on the transient characteristics of the engine itself. On the other hand, it is desirable to improve the speed response of engines for vehicle and ship because these engines often run in accelerating and decelerating modes. Not only in the case of a non-supercharged engine but also in a supercharged one, consequently, analyses have been made with attention paid to the speed response of engine to the change in fuel feed quantity or brake load⁽⁴⁾⁽⁵⁾. Under such an accelerating or decelerating running mode that

the engine speed changes near a stationary running state because of comparatively slight variation of the fuel feed quantity or brake load, an equation of motion for the engine rotating system is formulated using average values of the torque and speed of an engine during its one cycle as variables. And the responsiveness of engine speed has been followed by means of this equation in combination with the engine torque and brake load characteristics obtained from stationary operation. In spite of its simplicity, this method makes it possible to know such fundamental facts that the speed response remarkably depends on the characteristics of output and frictional torque, the inertial mass of the rotating system, etc. The fuel feed and the combustion processes of an engine, accordingly, the generation and transfer processes of its engine torque are intermittently repeated every one cycle, but Hazell, P. A. et al.⁽⁶⁾⁽⁷⁾ applied the so-called sampled data theory⁽⁸⁾ to the torque generation process of a diesel engine. Meanwhile Bowns, D. E.⁽⁹⁾ approximated the torque generating process with one in the form of finite-width and finite-amplitude pulse to analyse the speed control. In his analysis, Bowns changed periodically the rack of fuel injection pump and its frequency in a wide range, constructed a Bode diagram on the variation width of engine speed and made clear influences of the variational frequency and amplitude of rack, the torque generating frequency and gain, and the brake load damping coefficient. On the other hand, there is also a different example of analysis, in which the generation and transfer processes of engine torque are supposed to be continuous from a macroscopic point of view, and the thermal response lag of the frictional torque under transient operation, the influence caused by the intermittent processes of fuel feed and combustion, etc. are collectively taken into consideration as pri-

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mary response lag element ⁽⁵⁾⁽¹⁰⁾. This method is simple and convenient for gaining a general insight into the transient characteristics but it is necessary, for this purpose, to know the value of torque transfer time constant. In the present study, consequently, the torque transfer time constant was for the first time calculated back by using the value of speed time constant t_n , determined from frequency response or indicial response experiments, and the value of J/f given by the inertia moment J of the engine rotating system as well as the characteristic value f of engine and brake load being used, and the influences of various factors were made clear.

Among various transient response testing methods applied for studying the transient response, the indicial and frequency response methods were, in the present paper, used and compared with each other.

2. Method for Measuring the Torque Transfer Time Constant

Notations:

J : Inertia moment of a rotating system composed of an engine and a dynamometer
 t : Time or time constant
 T : Torque
 N : Engine speed
 X : Working position of fuel feed equipment
 Y : Load-regulating handle position of the dynamometer
 τ, n, x and y : Variations from the respective equilibrium points of T, N, X and Y , respectively
 Suffix 0: Value of the equilibrium point
 Suffixes e and l : Effective and brake load torques

On the assumption that the effective torque T_e is given as a function $T_e = T_e(X, N)$ and the infinitesimal variation approximation can be made, the variation of effective torque τ_e is

$$\tau_e = \left(\frac{\partial T_e}{\partial X}\right)_{N_0} \cdot x + \left(\frac{\partial T_e}{\partial N}\right)_{X_0} \cdot n \quad (1)$$

Even if the indicated torque immediately responds to a change in the working position of fuel feed equipment x , however, in connection with the temperatures of cylinder wall surface and lubricating oil, the value of frictional torque must have a thermal response lag from that during stationary operation of the same engine speed. Since, though discontinuous and repeated every cycle, in addition, the generation process of indicated torque is here treated as continuous, it is necessary to take into consideration a so-called response lag in which the influence of this treatment is also included. Let t_{ex} denote now the time constant of transfer response lag and instead of $\tau_e = (\partial T_e / \partial X)_{N_0} \cdot x$ write the following equation:

$$\tau_{ex} = \left(\frac{\partial T_e}{\partial X}\right)_{N_0} \cdot x - t_{ex} \frac{d\tau_{ex}}{dt} \quad (2)$$

Take further into consideration also a time lag of response concerning the temperatures of cylinder wall surface and lubricating oil, which is caused by the heat of mecha-

nical friction depending on the engine speed. Then instead of $\tau_{en} = (\partial T_e / \partial X)_{X_0} \cdot n$ it is possible to write the following equation by using the time constant t_{en} of the above-mentioned time lag:

$$\tau_{en} = \left(\frac{\partial T_e}{\partial N}\right)_{X_0} \cdot n - t_{en} \frac{d\tau_{en}}{dt} \quad (3)$$

From the infinitesimal variation approximation, in the next place, the variation τ_l of brake load torque of the dynamometer is

$$\tau_l = \left(\frac{\partial T_l}{\partial N}\right)_{Y_0} \cdot n + \left(\frac{\partial T_l}{\partial Y}\right)_{N_0} \cdot y \quad (4)$$

The equation of motion for a rotating system including an engine and a dynamometer can be written as follows:

$$J \dot{n} = \tau_e - \tau_l \quad (5)$$

2.1 Torque transfer response to the change in fuel feed quantity

Consider now $t_{en} = 0$ and accordingly include all in the time constant t_{ex} , because it could be experimentally confirmed that the time variation of driving torque was comparatively slight after a rapid change in the engine speed under motoring operation, and it is inevitable to evaluate a total response lag composed of two thermal ones t_{ex} and t_{en} due to the difficulty of complete separation of them and so on. When the Laplace transformation is then applied to Eqs. (1) to (5) and based on the result, a block diagram is constructed as shown in Fig. 1.

Fig. 1 Block diagram

Apply an equivalent transformation to the block diagram to obtain a transfer function $G_X(S)$

$$G_X(S) = \frac{N(S)}{X(S)} = \frac{\left(\frac{\partial T_e}{\partial X}\right)_{N_0}}{f} \cdot \frac{1}{(t_{ex}S + 1)(\frac{J}{f}S + 1)} \quad (6)$$

where

$$f = \left(\frac{\partial T_l}{\partial N}\right)_{Y_0} - \left(\frac{\partial T_e}{\partial N}\right)_{X_0} \quad (7)$$

[1] When the working position of fuel feed equipment is sinusoidally changed according to $x = x_0 \sin \omega t$.

The gain g_X and the phase ϕ_X of engine speed variation width are given by

$$g_X = 20 \log \frac{|G_X(j\omega)|}{|G_X(0)|} = 20 \log \frac{1}{\sqrt{(\frac{J}{f}\omega)^2 + 1} \sqrt{(t_{ex}\omega)^2 + 1}} \quad (8)$$

$$\phi_X = -\tan^{-1}(t_{ex}\omega) - \tan^{-1}(\frac{J}{f}\omega) \quad (9)$$

If the inertia moment J and the characteristic value f are known, it is possible to

determine analytically the torque transfer time constant t_{ex} from the gain g_x obtained from frequency experiments and Eq. (8). Since the inertia moment J and the characteristic value f can be determined by deceleration method⁽¹¹⁾ and from the characteristics experimentally obtained of brake load and effective torques for dynamometer and for engine, respectively, under stationary operation, it is possible after all to determine t_{ex} . This is the measurement principle of the frequency response method in the present study.

[2] When the working position of fuel feed equipment is changed stepwise.

It is possible to obtain the following relation

$$\frac{n(t_n)}{n(t_\infty)} = 1 - \frac{1}{e} \quad (10)$$

by applying the Laplace inverse transformation to the output $N(s)$ determined from Eq. (6), to an input $X(s)$. If the engine speed time constant t_n is experimentally known from indicial experiments, consequently, it is possible to calculate the torque transfer time constant t_{ex} from

$$t_{ex} = \frac{\frac{1}{f}(e^{-t_{ex}/t_n} - \frac{1}{e})}{e^{-t_{ex}/t_n} - \frac{1}{e}} \quad (11)$$

where, the inertia moment J and the characteristic value f can be known from above-mentioned method.

2.2 Torque transfer response to the change in the brake load

Considering the displacement y of dynamometer load-adjusting handle as input and the variation n of engine speed as output, respectively, if the working position of fuel feed equipment is fixed ($x=0$), then, it is possible to assume $t_x=0$ so that by applying the Laplace transformation to Eqs. (3) to (5) a block diagram can be constructed as shown in Fig. 2. Apply an equivalent transformation to the block diagram to obtain another transfer function $G_n(s)$

$$G_n(s) = \frac{G(N)}{G(Y)} = \frac{-\left(\frac{\partial T_l}{\partial Y}\right)_{N_0}(t_{en}s+1)}{t_{en}s^2 + \left\{J + t_{en}\left(\frac{\partial T_l}{\partial N}\right)_{X_0}\right\}s + f} \quad (12)$$

Fig. 2 Block diagram

[1] When the brake load is sinusoidally changed according to $y = y_0 \sin \omega t$.

In the case of

$$\left\{ \left(\frac{\partial T_l}{\partial N} \right)_{X_0} t_{en} - J \right\}^2 + 4J \left(\frac{\partial T_e}{\partial N} \right)_{X_0} t_{en} \geq 0$$

let $-1/\alpha$ and $-1/\beta$ denote the two roots of the following equation:

$$Z^2 + \left(\frac{1}{t_{en}} + \frac{\left(\frac{\partial T_l}{\partial N} \right)_{X_0}}{J} \right) Z + \frac{f}{t_{en}J} = 0 \quad (13)$$

then the gain g_n and the phase ϕ_n are given by

$$g_n = 20 \log \frac{|G_n(j\omega)|}{|G_n(j0)|} = 20 \log \frac{\sqrt{(t_{en}\omega)^2 + 1}}{\sqrt{(\alpha\omega)^2 + 1} \sqrt{(\beta\omega)^2 + 1}} \quad (14)$$

$$\phi_n = \tan^{-1}(t_{en}\omega) - \tan^{-1}(\alpha\omega) - \tan^{-1}(\beta\omega) \quad (15)$$

If the value of gain g_n at a certain angular velocity ω is known from frequency experiments, accordingly, it is possible to determine the time constant t_{en} as the roots of a quadratic equation, derivable from Eq. (14) and which of these two roots fits the problem can be judged on the basis of comparison with experimental values of phase lag. As can be seen from the values of $(\partial T_l/\partial N)_{X_0}$ and $(\partial T_e/\partial N)_{X_0}$, the value of t_{en} is small in general, so that the condition

$$\left\{ \left(\frac{\partial T_l}{\partial N} \right)_{X_0} t_{en} - J \right\}^2 + 4J \left(\frac{\partial T_e}{\partial N} \right)_{X_0} t_{en} < 0$$

is only rarely satisfied. Consequently, this case was not treated in the present paper.

[2] When the brake load is changed stepwise.

If the engine speed time constant t_{en} is experimentally given, consequently, it is possible to calculate the torque transfer time constant t_{ex} from

$$t_{ex} = \frac{\frac{1}{\alpha} - \frac{1}{\beta} + \frac{1}{\beta} e^{-t_{ex}/t_n} - \frac{1}{\alpha} e^{-t_{ex}/t_n}}{\left(\frac{1}{\alpha\beta} \right) (e^{-t_{ex}/t_n} - e^{-t_{ex}/\beta})} \quad (16)$$

3. Experimental Apparatus and Method

Specifications of the engines tested are shown in Table 1. The experimental apparatus is, as shown in Fig. 3, composed of

Table 1 Specifications of test engines

Symbol	E-252	E-353	E-567	E-815
Ignition method	Spark	Compression	Compression	Compression
Cycle number	4	4	2	4
Type of combustion chamber	Side valve type	Pre-combustion chamber	Swirl chamber	Pre-combustion chamber
Cylinder bore X stroke mm	72 X 62	78 X 80	85 X 100	95 X 115
Stroke volume cc	252	353.4	567	815
Compression ratio	6.2	23	23	20
Inertia moment of rotating system kg·m ²	0.2118	0.1775	0.8424	1.971

(1) a round nozzle for measuring the intake air amount in stationary operation, (2) a surge tank, (3) a manometer, (4) a fuel flowmeter, (5) a dynamometer, (6) an intake air heater, (7) a thermometer, (8) and (9) devices for changing sinusoidally the working position of fuel feed equipment and the brake load torque of dynamometer, respectively, (10) and (11) their displacement indicators, respectively, (12) an engine speed indicator, (13) a laminar-flow type instantaneous air flowmeter, etc. Determined preliminarily by the deceleration method, the inertia-moment J of a rotating

When ΔT_e is, in this case, kept constant independently of N_0 , the variation width of working position X_0 depends on N_0 , when x_0 is kept constant, T_{e0} depends on N_0 . In either case, the time constant as shown in Fig. 5, decreases with an increasing N_0 and converges to a constant value $t_{ex}=0.2$ to 0.3 sec. within a range of $N_0=1800$ rpm. If a comparison is made at the same N_0 , the value of t_{ex} decreases with an increasing X_0 and consequently the set engine torque T_{e0} , corresponding to X_0 . As for possible causes of this, the following is conceivable.

When X_0 is kept constant, the engine tested has such a steady operation characteristics that T_{e0} increases in proportion to N_0 within a range of the present experiments. Even if the variation ratio x_0/X_0 is kept constant, for this reason, $\Delta T_e/T_{e0}$ decreases with an increasing N_0 . Similarly, $\Delta T_e/T_{e0}$ also decreases with an increasing X_0 or T_{e0} while N_0 is kept constant. In addition, the time interval between two successive generated pulses of the engine torque is shortened with an increasing N_0 . These factors decrease the torque transfer lag due to unsteadiness and intermittence.

Since the turbulence of mixture in the cylinder increases in proportion to N_0 , the mixture formation is promoted and the combustion process and the heat transfer are facilitated. If the temperatures of engine wall t_{w0} and cooling water t_{cw0} are kept constant, for this reason, those of internal wall and frictional part in the engine rise, so that not only the frictional torque T_{f0} , but also the variation ratio $\Delta T_f/T_{f0}$ decreases. This reduces the time constant t_{ex} of the thermal response lag of the frictional torque. At constant N_0 and X_0 , the value of t_{ex} increases with an increasing x_0 or ΔT_e . Since in this case, the variation width ΔG_f of fuel feed quantity increases in proportion to x_0 , acceleration and deceleration of the engine become relatively higher. It appears, on the other hand, that so-called unsteadiness (difference between the performances of steady and transient operations under the same condition) becomes remarkable, because the follow-up quality of thermal factors—intake air quantity, scavenging process, combustion state, frictional torque, etc.—is inferior due to the large thermal capacity of engine. This is similar to a fact that the value of t_{ex} determined by the indicial response method (Mark I in the figure) is, as shown in Fig. 6, larger than that determined by the frequency response method (Mark:F) and the difference between both the values increases with a decreasing N_0 . When the determination of t_{ex} is carried out by the former method, its value (Mark:R-I) under deceleration operation by means of stepwise decrease in quantity of fuel fed is larger, to some degree, than that (I) under acceleration operation by stepwise increase. Fig. 5 comprises also the experimental result, obtained by suddenly increasing the carburetor throttle valve opening C of the gasoline engine tested E-252. In general, a gasoline engine has a thermal capacity of itself, which is

Fig. 6 Comparison of frequency method (F) and indicial method (I)

smaller than that of a corresponding diesel engine, but since the intake air quantity of the former engine is not constant and the fuel feed quantity cannot follow up, a response time lag of the mixture formation is caused. It seems that this fact contributes to the similar result.

4.1.2 Influence of cylinder wall temperature t_{w0} , cooling water temperature t_{cw0} , intake air temperature t_{a0} and intake air amount G_{a0}

An increase in t_{w0} , t_{cw0} and t_{a0} makes the engine temperature rise, which shortens the time constant t_{ex} . Since the set intake air amount G_{a0} is lowered, on the contrary, the residual gas increases to make larger the thermal capacity of charging gas in the cylinder, resulting in a combustion temperature drop. As a result, the engine temper-

Fig. 7 Time constant t_{ex} vs. temperatures t_{w0} , t_{cw0} , t_{a0} of cylinder wall, cooling water, intake air

ature also falls, so that the effect of the increase in t_{w0} , t_{cw0} and t_{a0} is cancelled. For this reason, it is possible to observe a tendency that the value of t_{ex} determined by the indicial and frequency response methods increases, in spite of its small amount, in direct and inverse proportion to t_{w0} , t_{cw0} and t_{a0} (Fig. 7), on the one hand and to G_{a0} (Fig. 8), on the other hand, respectively.

Fig. 8 Time constant t_{ex} vs. intake air amount G_{a0} , exhaust gas recirculation ratio EGR_0

4.1.3 Influence of EGR and additional fuel

If it is possible to increase the quantity (EGR %) of exhaust gas recirculation, which is useful for decreasing the concentration of nitrogen oxides NO_x , then the thermal capacity of charging gas in the cylinder will be increased, with the combustion temperature down, the combustion slow down, etc., so that the engine temperature drops to increase the value of t_{ex} (line of $M=0$ %, Fig. 8.B). When methanol fuel is further fed into intake pipe in order to reduce the exhaust gas emission and to substitute the fuel, the temperatures of the combustion and cylinder wall drop so that the thermal responsiveness deteriorates and the value of t_{ex} increases in proportion to the quantity of auxiliary fuel added (M : ratio of energy added, see Fig. 8). When methanol fuel is fed into the intake pipe, the combustion temperature in a system of intermittent feed only during the suction stroke is lower, due to latent heat of methanol vaporized in the intake pipe, than the combustion temperature in another system of continuous addition, so that t_{ex} is longer (comparison between the lines F and P-F in Fig. 8).

4.2 Experiment on torque transfer to the change in brake load

4.2.1 In the case of diesel engine

Fig. 9 shows the time constant t_{en} of torque transfer to the change in load-regu-

Fig. 9 Time constant t_{en} vs. set rack position X_0 of fuel pump

lating handle. The value of t_{en} increases in proportion to the variation width y_0 and its value equals to about 0.1 to 0.2 sec. within the range of the present experiment. Although the variation of engine speed is large, in this case, the flow rate of fuel fed every cycle changes little, so that there is no such response lag, as caused by a change in fuel feed quantity as mentioned above, resulting in comparatively slight unsteadiness of the engine. It seems that t_{en} is smaller than t_{ex} because of this unsteadiness.

4.2.2 In the case of gasoline engine

The influence of the set carburetor opening C_0 and engine speed N_0 on t_{en} is, as shown in Fig. 10, comparatively slight.

Fig. 10 Time constant t_{en} vs. set carburetor opening C_0

The value of t_{en} increases, however, in proportion to the variation width y_0 of load-regulating handle and the set excess air ratio λ_0 . The influence of the latter λ_0 , in particular, coincides qualitatively with a fact that the time constant t_{ex} of a diesel engine is in inverse proportion to X_0 . The value of t_{en} of a gasoline engine comprises the influence of response lag of the mixture formation and since the ratio of fuel liquid film flow in the intake pipe and its response lag depends on λ_0 , it appears that the value of t_{en} is affected by λ_0 . Even if λ_0 is constant, on the other hand, the response lag of fuel liquid film flow is deteriorated in proportion to intake pipe length L_i , so that the value of t_{en} increases as shown in Fig. 11. In general, the time constant t_{en} under deceleration operation is larger than that under acceleration operation (see Fig. 11). Also in this case, the value of t_{en} is, as shown

Fig. 11 Time constant t_{en} vs. intake pipe length L_i

Fig. 12 Time constant t_{en} vs. set carburetor opening C_0

in Fig. 12, proportional to C_0 , λ_0 and y_0 , and increases in inverse proportion to N_0 as far as C_0 is small.

5. Conclusions

From the response of engine speed to a sinusoidal or stepwise change in quantity of fuel feed and brake load, the authors calculated back the time constant of torque transfer and showed definitely its relationship with the operating conditions, which can be summarized as follows:

[A] Torque transfer to the change in fuel feed quantity

(1) The transfer of effective torque comprises a certain response time lag, which is caused by thermal response lag of the frictional torque, etc. and the intermittency of torque generation and if its response is considered to be of first-order lag element, its time constant of torque transfer is about 0.2 to 0.6 sec.

(2) The time constant t_{ex} of torque transfer decreases with an increasing engine speed N_0 at the setting, decreasing the fuel quantity and consequently decreasing the set working position of fuel feed equipment, for example, the set rack position X_0 (or T_{e0}) of the fuel pump and decreasing the variation width x_0 (or ΔC) of the fuel feed quantity.

(3) Although the relationship between the

value of t_{ex} determined by the frequency response method and various factors— N_0 , X_0 , t_{CWO} etc.—is approximately the same as the relationship obtained by the indicial response method, the former value of t_{ex} is smaller by about 0.1 to 0.2 sec. than the latter. It appears that this is caused by a fact that the rate of change in engine variation speed (acceleration or deceleration) for the former is lower than that for the latter. In any case, the time constant t_{ex} under deceleration operation is larger than that under acceleration operation.

[B] Torque transfer to the change of brake load

(4) In a diesel engine, the response of torque transfer to the change in brake load also comprises a response time lag. The value t_{en} of its time constant is smaller than the time constant t_{ex} to the change in fuel feed quantity and its value equals to about 0.1 to 0.2 sec. Moreover, the value of t_{en} increases in proportion to the set fuel feed quantity X_0 and the variation width y_0 of brake load.

(5) The time constant t_{en} of a gasoline engine is approximately equal to that of a corresponding diesel engine and though only slightly affected by the set carburetor opening C_0 and the engine speed N_0 , the value of t_{en} increases in proportion to y_0 , the excess air ratio λ_0 and the intake pipe length L_i . In any case, further, the value under decelerating operation is larger than that under accelerating operation.

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