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SPEED RESPONSE TO THE LOAD FLUCTUATION IN A FOUR-CYCLE GASOLINE ENGINE

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The authors tried to make experimentally clear the response of engine speed to stepwise increasing, decreasing or sinusoidally fluctuating load. Based on a simplified model devised from the standpoint of the control theory, analysis was carried out with digital computer and its results obtained coincide well with those of experiment, so that it could be confirmed that it is possible to simulate the speed response to variation of the load.

1. Introduction

Four-Cycle Gasoline Engines are widely used in vehicle and construction machine, for agriculture etc. and many investigators are actively engaged in its performance improvement. However, these investigations most concern the performance improvement during stationary running and there are comparatively few researches concerning those during transient running such as starting, accelerating and decelerating as well as load fluctuation [1][2]. The behavior of engine performance in transient running condition can be made clear by investigating in detail the transient characteristics in each transmission element, that is, fuel feed and combustion processes, the moving system of engine, friction loss, etc..

However, the progress of research concerning the transient running characteristics is prevented by the under development of a technology, which makes it possible to measure accurately and simply the instantaneous values of various factors, affecting the transient characteristics of an engine. The authors noted the fluctuation in engine speed, particularly easily measurable in order to study systematically the transient running characteristics of an engine and, in this research, tried to make experimentally clear the response of engine speed to stepwise increasing, decreasing or sinusoidally fluctuating load. The experimental results obtained are described in the following.

2. Experimental Apparatus and Method

2.1 Experimental apparatus

Experiment was carried out on a four-cycle gasoline engine with carburetor, of which principal dimensions are given in Table 1, whereas Fig.1 shows the experimental arrangement, which is composed of a round nozzle 2, a surge tank 1, and a manometer 3 for measuring the intake air in stationary running, a laminar-flow type flowmeter 4, and a differential-pressure type transducer 18 for measuring

Table 1 Specifications of test engine.

Cycle	4 (S.V)
Bore x Stroke (mm)	72 x 62
Stroke Volume (cc)	252
Compression Ratio	6.2
Maximum Torque / Engine Speed (N·m/rpm)	13.23 / 3000
Ignition Advance (rad)	0.127
Fuel used	Non-lead Gas

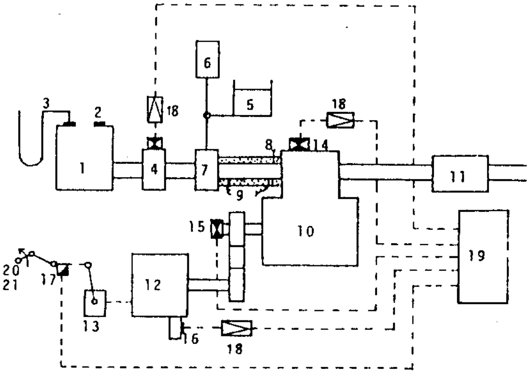

Fig.1 Experimental apparatus.

an instantaneous value of the intake air, a fuel flowmeter 6, a intake pipe heater 9, a intake pipe wall thermometer 8, the tested engine 10, an indicator 14, a tachometer 15, an eddy-current type electric dynamometer 12, a strain gauge 16 for measuring the torque, a crank mechanism for transforming the load torque of the dynamometer into a sinusoidal form, the displacement gauge 17 of a load-adjusting handwheel, etc..

Since the authors intended to research the response of engine speed to load fluctuation, they used the air-cooled eddy-current type dynamometer, which has a small inertial mass and makes it possible to change simply the load, and determined by the deceleration method [3] the inertia-moment of a rotating system composed of the tested engine and the dynamometer, resulting in $J=0.2118$ kg•m^2.

2.2 Experimental method

Measured first engine speed, intake air, fuel flow rate and engine output while the engine stationary running in predetermined conditions. With a carburetor opening kept constant, then, increase or decrease stepwise the load current (through the position of the load-adjusting handwheel) of the dynamometer by operating a spring mechanism. In case the load is to be changed sinusoidally, change the fluctuating frequency into eleven steps within a range from 0.1 to 10.0 rad/s with the crank mechanism and a varying-speed motor and record continuously the torque and the speed of engine corresponding to these steps on a data-recorder.

Reproduce the data recorded on an electromagnetic oscillograph to determine the time constants of the torque and the engine speed. Although the response of the instantaneous engine tachometer itself is to be separately investigated in this case, the time constants of the tachometer used are 5 to 15 and 25 to 45 ms for building-up and building-down transients, respectively. The experiment was carried out in various combinations such as the initial engine speeds $N_0=2400$, 2700, 3000 rpm, the carburetor opening $C_0=1/4$, 2/4 and 4/4, the initial air-fuel ratio $(A/F)_0=11.8$, 14.7 and 16.2, the intake pipe length $L_i=18.6$, 31.1 and 60.6 cm and the intake pipe wall temperature $t_w=10$, 30, 50 and 70 °C.

The stationary-running characteristics of the effective engine torque T_e, of the friction torque T_r and of the intake air G_a are shown in Fig.2 and 3, whereas that of the dynamometer load torque T_l as shown in Fig.4.

3. Experimental Results and Discussion

Notations:

J: Inertia-moment of a rotating system composed of the engine and the dynamometer (kg•m^2),

t: Time or time constant (sec),

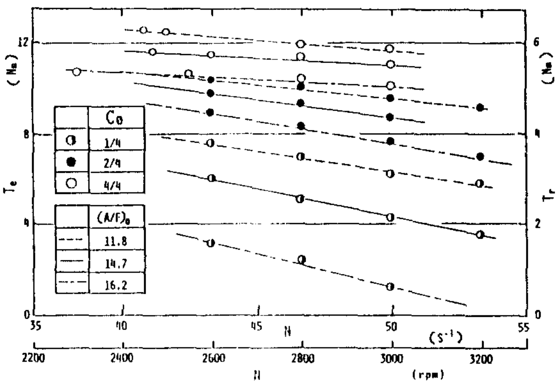

Fig.2 Characteristics between effective engine torque T_e or friction torque T_r and engine speed N.

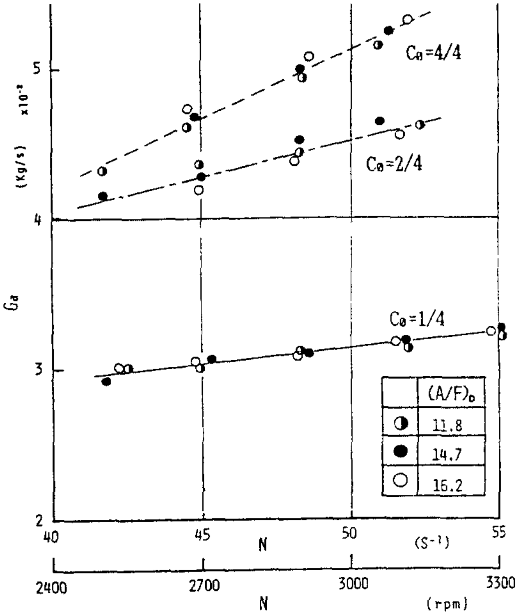

Fig.3 Characteristics between intake air G_a and engine speed N.

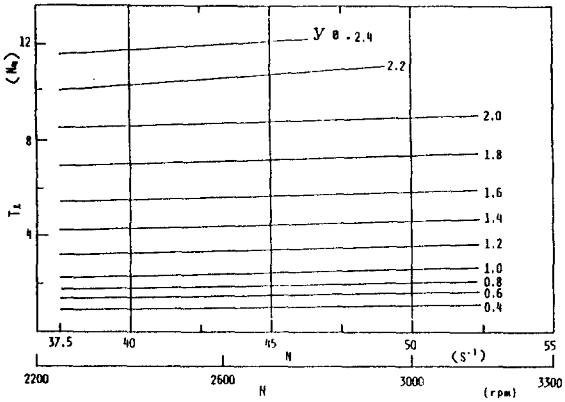

Fig.4 Characteristics between load torque T_l and engine speed N.

N: Engine speed (rad/s),
G: Flow rate (kg/s),
T: Torque (N m),
M: Air fuel ratio,
n, g, and m: Variations from the respective equilibrium points of N, G T and M, respectively,
Suffix symbols $_0$: Value of the equilibrium point, respectively.

3.1 Preliminary discussion on the speed response

The response of carburetor gasoline engine speed depends not only on the engine output characteristics but also on the friction loss characteristics, the dynamometer load characteristics, the inertia-moment of the engine and the dynamometer etc. and the engine output characteristics is in turn affected by the quality and the quantity of mixture in the cylinder. Although a part of fuel fed from the carburetor floats in the intake air and enters into the cylinder together with the latter, another part flows into the cylinder in a form of liquid film, so that the mixture forming process during transient running is remarkably by the behavior of this liquid film fuel. Moreover, it is possible only with many difficulties even for stationary running to measure directly not only the formation process of mixture in the cylinder but also the friction loss torque itself and even its measuring method is not yet established for transient running.

To simplify the problem, here, the process is considered to be approximately continuous, the standpoint of the control theory is applied to the analysis of speed response to discuss the problem in the following while the change in load y and that in engine speed n being taken as input and output, respectively. The variables N, G, T and M are sums of equilibrium quantities N_0, G_0, T_0 and M_0, respectively, and variations n, g, τ and m, respectively, and since, in the research, experiment is carried out while the carburetor opening being kept constant, it is possible to assume that the intake air and fuel, the air-fuel ratio, the effective and the load torque are given by functions $G_a=G_a(N)$, $G_f=G_f(G_a)$, $M=M(G_a,G_f)$, $T_e=T_e(N,M)$ and $T_l=T_l(N,Y)$, respectively. If infinitesimal variation approximations of G_a, G_f, M, T_e and T_l are possible, then the respective variations are given by the following equations, respectively:

$$g_a=(\partial G_a/\partial N)_0\cdot n \qquad \ldots(1)$$

$$g_f=(\partial G_f/\partial G_a)_0\cdot g_a \qquad \ldots(2)$$

$$m=(\partial M/\partial G_a)_{Gf0}\cdot g_a+(\partial M/\partial G_f)_{Ga0}\cdot g_f \qquad \ldots(3)$$

$$\tau_e=(\partial T_e/\partial N)_{M0}\cdot n+(\partial T_e/\partial M)_{N0}\cdot m \qquad \ldots(4)$$

$$\tau_l=(\partial T_l/\partial N)_{Y0}\cdot n+(\partial T_l/\partial Y)_{N0}\cdot y \qquad \ldots(5)$$

It appears however that the flow rate of intake fuel cannot follow any rapid change in intake air because of the inertia of liquid column in the jet pipe path, of fuel feed delay in the intake pipe, etc..

Then let us assume that the fuel supply process has approximately a first order lag with its time constant t_f and replace Eq.(2) with the following:

$$g_f=(\partial G_f/\partial G_a)_0\cdot(\partial G_a/\partial N)_0\cdot n-t_f\cdot(dg_f/dt) \qquad \ldots(6)$$

Based on a fact that the friction loss torque has a thermal response lag, it can be supposed that the effective torque also shows some lags of response to the changes in engine speed and air fuel ratio. For this reason, let us replace $\tau_{en}=(\partial T_e/\partial N)_{M0}\cdot n$ and $\tau_{em}=(\partial T_e/\partial M)_{M0}\cdot m$ with following:

$$\tau_{en}=(\partial T_e/\partial N)_{M0}\cdot n-t_{en}\cdot(d\tau_{en}/dt) \qquad \ldots(7)$$

$$\tau_{em}=(\partial T_e/\partial M)_{N0}\cdot m-t_{em}\cdot(d\tau_{em}/dt) \qquad \ldots(8)$$

If the torque-generating process can be considered to be continuous, the equation of motion of the rotating system is given by

$$J\cdot n=\tau_e-\tau_l \qquad \ldots(9)$$

When Eqs. (3) and (5) (9) are Laplace-transformed to draw a block diagram, which is shown in Fig.5. From Fig.5, a transfer function N(s)/Y(s) can be easily obtained and since Y(s) is given by $Y(s)=k/s$ or $Y(s)=\omega/(s^2+\omega^2)$ if the displacement y of the dynamometer load

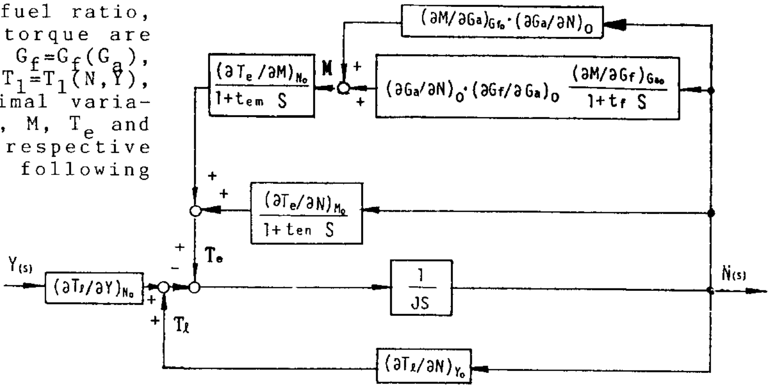

Fig.5 Block diagram (input: load, output engine speed).

adjusting handwheel changes in the form of step and sinusoidally, respectively, it is possible to determine also analytically the behavior of engine speed n. When a digital computer is used, in addition, it is possible to examine how various factors included in the block diagram, Fig.5, affect the behavior of engine speed n. In this case, the characteristic values of engine $(\partial G_a/\partial N)_0$, $(\partial G_f/\partial G_a)_0$, $(\partial T_e/\partial N)_{M0}$, $(\partial T_e/\partial M)_{N0}$, $(\partial M/\partial G_f)_{Ga0}$ and $(\partial M/\partial G_a)_{Gf0}$ can be determined from the experimental values of the engine tested under stationary running and $(\partial T_l/\partial N)_{Y0}$ and $(\partial T_l/\partial Y)_{N0}$ from the load characteristic values of the dynamometer tested.

Although it is difficult to estimate precisely the values of the time constants t_{em}, t_{en} and t_f, it becomes possible to estimate them conversely from the behavior of engine speed n.

3.2 Step response

The time-dependent behaviors of the engine speed and the effective engine torque always increase or decrease approximately as a first-order lag element. The time constant of speed t_n and of torque t_{en}, determined from the behaviors are shown in Figs.6 to 13 as function of the carburetor opening C, of the excess air ratio λ, of the intake pipe wall temperature t_w, of the intake pipe length L_i, of the variation width y_0 of the dynamometer load-adjusting handwheel, etc., set at starting of stepwise decrease or increase of load. As can be seen from these figures, the time constant t_{en} of the transfer response lag of effective torque is decreased to improve the follow-up quality with increasing set opening of carburetor C_0 (Figs.6 and 7), with increasing mixture concentration, that is, decreasing excess air ratio λ_0 (Figs. 10 and 11) and with decreasing intake pipe length (Fig.12). This transfer response lag of effective torque is induced by a fact that fuel liquid-film flowing in along the intake pipe inside wall cannot follow up the change in intake air due to its inertia and this causes a response lag in quality of mixture in the cylinder. As for this response lag of liquidfilm flow, the velocity of intake air flow becomes higher with increasing carburetor opening and as a result the velocity of fuel liquid-film flowing on the inside wall is increased and with increasing mixture concentration the fuel flow rate is increased, resulting in thicker liquid-film of it and also in higher velocity of the flow. It appears that, for this reason, the follow-up quality of fuel flow rate to the variation in intake air becomes better and the response lag of effective torque also shorter under the condition of higher velocity of fuel liquid-film flow.

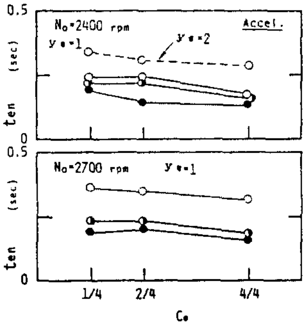

Fig.6 Time constant t_{en} of effective torque vs. set opening of carburetor C_0 (acceleration).

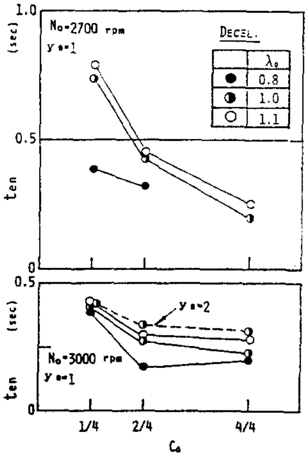

Fig.7 Time constant t_{en} of effective torque vs. set opening of carburetor C_0 (deceleration).

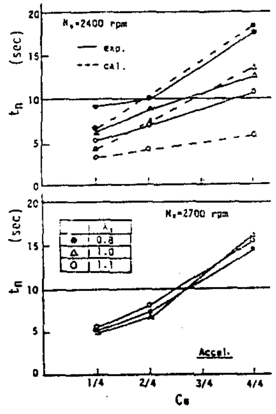

Fig.8 Time constant t_n of engine speed vs. set opening of carburetor C_0 (acceleration).

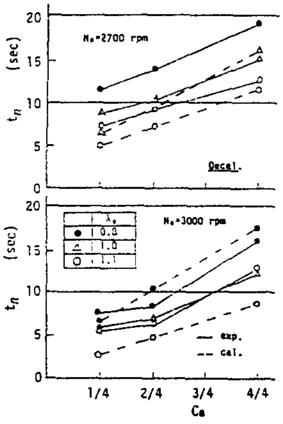

Fig.9 Time constant t_n of engine speed vs. set opening of carburetor C_0 (deceleration).

Since a shorter length of the intake pipe makes in addition shorter the travelling distance of fuel liquid-film flow, it appears that the response quality of fuel liquid-film flow is improved. Except the influence of change in the carburetor opening C during decelerating running (Fig.7), those of various factors on the time constant t_{en} of effective torque are comparatively slighter, the amount being about 0.2 to 0.4 sec.. On the other hand, the time constant t_n of engine speed response lag tends to be increased as the engine speed variation width, increases with larger carburetor opening (Figs.8 and 9), with smaller excess air ratio (Figs.10 and 11) and with smaller intake pipe length (Fig. 12). In this case, the time constants of torque t_{en} and of speed t_n do not al-

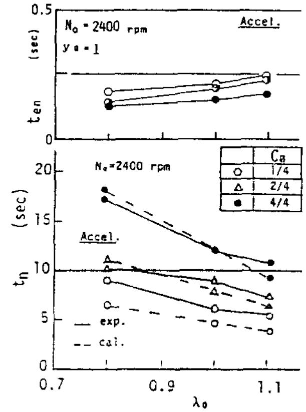

Fig.10 Time constant t_n and t_{en} vs. set excess air ratio λ_0 (acceleration).

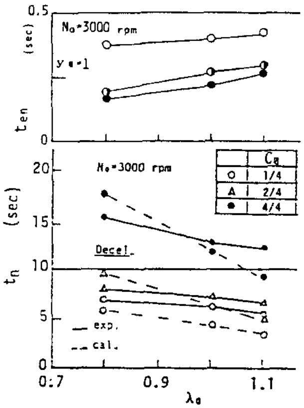

Fig.11 Time constant t_n and t_{en} vs. set excess air ratio λ_0 (deceleration).

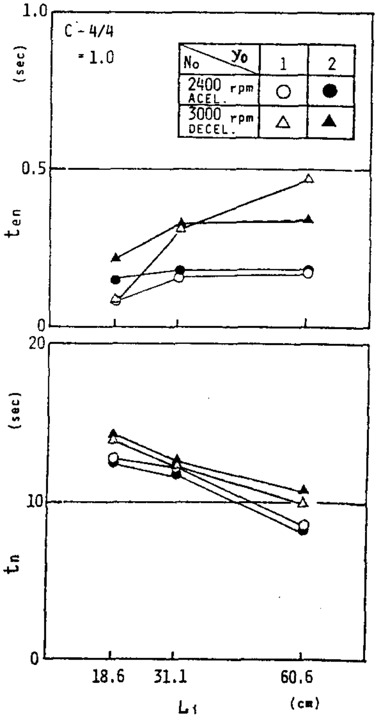

Fig.12 Time constant t_n and t_{en} vs. set intake pipe length L_i.

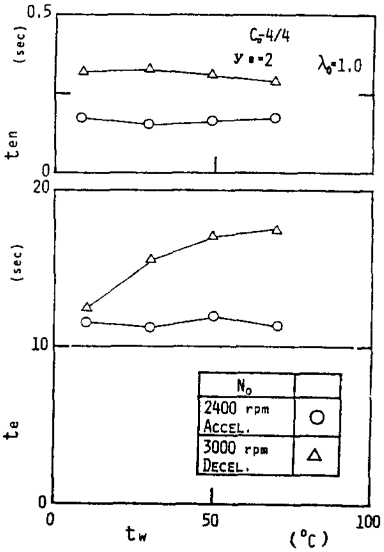

Fig.13 Time constant t_n and t_{en} vs. set temperature of intake pipe wall t_w.

most change (Fig.13) in accelerating even by heating the intake pipe wall, whereas both the values of t_{en} and t_n in decelerating running are larger than those in accelerating, respectively (comparison of Figs.6 and 8 with Figs.7 and 9, respectively), and t_n is considerably increased as the intake pipe wall is heated (Fig.13). In this way, the time constant t_n of engine speed remarkably depends on the setting conditions at starting of acceleration or deceleration, because the performance values of engine changes according to the running conditions. Fig.8 shows, besides the other data, the results of analysis with digital computer, which coincide qualitatively well with those of experiment, and based on this coincidence it can be seen that the consideration described in the preceding section from the standpoint of the control theory is useful for making clear the speed response to load variation.

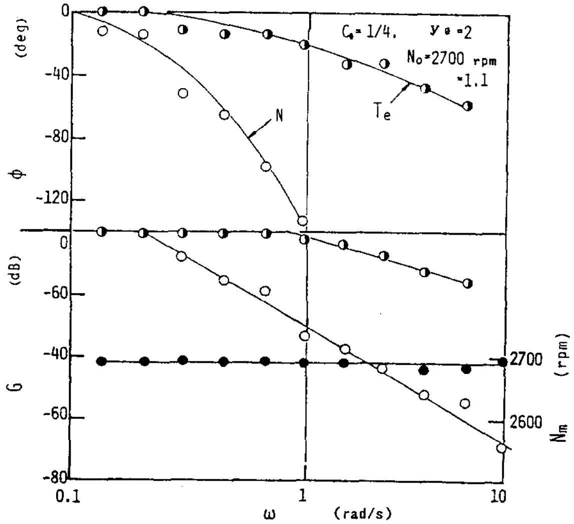

Fig.14 Bode diagram of engine speed and effective engine torque.

3.3 Frequency response

Fig.14 shows a gain curve of engine speed, which is drawn from the variation

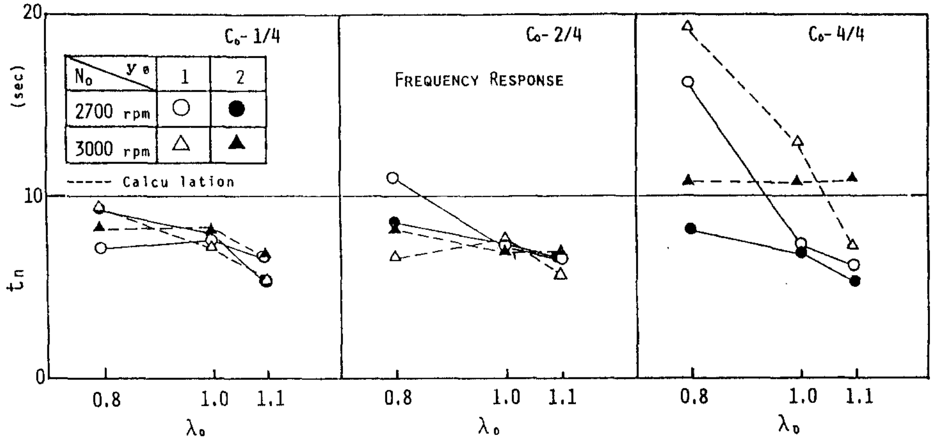

Fig.15 Time constant t_n vs. set excess air ratio λ_0 (frequency method).

width of engine speed, produced by changing the dynamometer load-adjusting handwheel sinusoidally according to $y=y_0 \sin \omega t$ and the time constant of speed calculated on the basis of this is shown in Fig.15.

According to Fig.14, the gain of variation width, marked with **o**, of engine speed decreases from about $\omega=0.15$, whereas that marked with ●, of the effective torque remains zero up to about $\omega=0.8$. This means that the time constant of the effective torque is considerably smaller, whereas that of the speed considerably larger and is correlated with the results obtained by the method of step response, described in the preceding section.

In this case, the average engine speed has a tendency to decrease in proportion to the angular frequency ω. As can be seen from Fig.15, the time constant of speed t_n determined from the frequency response becomes larger with increasing carburetor opening and excessively increasing air fuel ratio. This tendency coincides qualitatively well and also quantitatively almost with the result obtained in the preceding section by the method of step response. Since the input $Y(s)$ can be here written as $Y(s)=\omega/(s^2+\omega^2)$, this can be also easily analyzed with digital computer and Fig.15 also shows an example of its results, which coincides well with the corresponding experimental values. Consequently, it can be seen that the response lag caused by a stepwise change of the load is the same as that caused by a periodic variation.

4. Conclusion

Among the transient running characteristics of a four-cycle gasoline engine with carburetor, the authors took up, for the time being, the response of engine speed to a stepwise or a periodic change respective variation of the load, they investigated it experimentally and considered the results obtained from the standpoint of the control theory, the consideration being able to be summarized as follows:

(1) When the load stepwise decrease (the engine is accelerated) or increases (decelerated), the engine speed behaves as if it is a first-order lag element, so that the time constant of speed becomes larger and the speed response worse with increasing carburetor opening at the start of its variation, with decreasing intake pipe length and in general with increasing load variation width. Also in general the time constant of speed during decelerating running is larger than that during accelerating running, that is, the response quality is worse during the former. When the intake pipe wall temperature is raised, the time constant of speed to stepwise decrease of load does not almost change, whereas that during stepwise increase becomes considerably larger.

(2) While speed response to a preiodic change of the load behaves as if it is a first-order lag element, the time constant of speed determined by the so-called frequency response method also coincides even quantitatively well with that determined by the step response method and also as for its connection with various factors, similar results could be obtained.

(3) Based on a simplified model devised from the standpoint of the control theory, analysis was carried out with digital computer and its results obtained coincide well with those of experiment, so that it could be confirmed that it is possible to simulate the speed response to variation of the load.

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