Paper No. 84—0273

Low Speed Hunting of Pneumatically Governed Compression-Ignition Engine*

(2nd Report, Stability Criticism of the Closed Engine-Governor Loop Based on Measured Frequency Responses of the Two Open Systems Composing the Loop)

By Yoshihiko KAWAZOE**

The author showed in the previous report that the key factor must be the phase lag of the governing pressure taken at a narrrow passage called subventuri beside a throttle valve, because the hunting disappears when the phase lag is minimized by displacing the pressure source to the common intake duct just down the throttle valve and the subventuri. In the present work, he experimentally determines the frequency response of the engine system and the one of the pneumatic governor system composing a closed loop, in order to verify the existence of hunting under the subventuri pressure control and its non-existence under the suction pressure control.

Key Words: Vibration, Low Speed Hunting, Pneumatic Governor, Compression-Ignition Engine, Subventuri, Suction Pressure, Fuel Injection Pump, Stability

1. Introduction

In a pneumatically governed compression-ignition engine its idling speed can not remain constant over some speed range, and in consequence a low frequency noise of its own occurs. This fluctuation of the engine speed is called low speed hunting (1)(2)(3). A pneumatic governor controls the fuel delivery displacing the fuel control rack with the reduced pressure taken at a narrow passage called subventuri beside a throttle valve.

It was stated in the previous report (3) that the key factor must be the phase lag of the governing pressure taken at the subventuri, because the hunting disappears when the phase lag is minimized by displacing the pressure source to the common intake duct just down the throttle valve and the subventuri. The present paper first shows a few experiments for investigating the differences of dynamic characteristics between the subventuri pressure and the suction pressure. Further, to reveal the effects of the phase differences between those two pressures upon hunting, the closed engine-governor loop is supposed to be divided into two open loop systems : 1) an engine system through which the engine speed responds to the displacement of the fuel control rack and 2) a pneumatic governor system through which vice versa. The frequency responses of the two open systems are measured on the tested engine without hunting under suction pressure control with its pump control rack given a low frequency harmonic excitation by a shaker through the rack spring : 1) the amplitude-and phase-responses of the engine speed to the displacement of the pump control rack and 2) the amplitude and phase of the control rack of an added fuel injection pump supplied with the governing pressure but not with fuel called a dummy pump responding to the engine speed. Application of the stabillty criteria to the closed engine-governor loop demonstrates the occurrence of hunting under the subventuri pressure control and its non-occurrence under the suction pressure control.

2. Experimental Study on the Characteristics of the Reduced Pressure for Rack Control

As shown in Fig.1, a dummy injection pump is added to the engine which is driven without hunting under suction pressure control. To the control rack of the actual injection pump, almost the same motion as the one at the low speed hunting is given by a shaker through the rack spring at 1.0, 1.5, 2.0 and 3.0 Hz. Responses of the subventuri pressure and the suction pressure to the engine speed fluctuation were recorded respectively, and the phase lag of each pressure relative to the speed fluctuation was derived using a digital analyzer. In Fig.2 are shown those phase lags versus the excitation frequency, where P_1 is the subventuri pressure without hose connec-

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tion to the diaphragm chamber of the dummy pump, while P_1', P_3' are the subventuri pressure and the suction pressure with connection to the diaphragm chamber respectively. It may be noted here that the subventuri pressure P_1' is more delayed than the suction pressure P_3'. The phase lag of P_1' is 25～30° at 2 Hz which is the hunting frequency of the tested engine, whereas that of P_3' is 6～7°.

In Fig.3, the throttle valve beside the subventuri is fully opened and a ball valve is added upstream as an adjustable throttle for pneumatic speed control. In this case also occurred a low frequency hunting but in a narrower speed range (740 ～780 rpm) with smaller amplitudes of fluctuation than those under the normal subventuri pressure control. The throat area of the throttle valve including the subventuri is smaller than that of the intake duct by 30 %, having an equivalent diameter of 39 mm.

In Fig.4 a simulated subventuri combined with two ball valves is attached to the intake manifold instead of the throttle valve-subventuri assembly. This alternative subventuri is made of a steel plate of 20 mm thick with a straight circular hole of 10 mm bore. The hunting phenomena remain the same in spite of these changes. As the pressure tap I in Fig.1 projects into the subventuri passage by 2 mm, the effect of tap projection on the hunting is examined with a simulated venturi system with no influence recognized up to 3 mm projection.

3. Investigation of Stability

3.1 Procedure of determining the frequency response

In order to verify the divergence of subventuri pressure control and the convergence of suction pressure control, frequency responses of the two open systems composing the engine-governor loop are measured on the driven engine combined with a dummy pump mentioned above. The behavior of the closed loop system based on those data is compared with that of the actual system. Although the hunting motion of each element of the system comprises a component of the hunting frequency and a component of a higher frequency caused by a suction stroke of each piston, the component of the hunting frequency changes almost sinusoidally owing to the engine inertia ; thus the nonlinear relation between output and input of the system is considered to be linear with reference to the frequency response, i.e., when an approximately sinusoidal displacement is given to the fuel control rack as an input signal, the component of the same fundamental frequency component of the steady output is compared with the input.

When the reciprocating displacements of 1.0, 1.5, 2.0 and 3.0 Hz were given to the control rack of the injection pump by a shaker through the rack spring at each engine speed, 1) the amplitude ratios and phase differences of the engine speed response to the low frequency displacement of the control rack and 2) those of control rack response of the dummy pump to the engine speed were derived using a digital analyzer. On the basis of the composition from these results, the stabilities of the closed loop control at each engine speed were discriminated.

3.2 Frequency characteristics of the engine system

Here we take a series connection between the displacement of the fuel control rack, fuel injection, torque and engine speed as an engine system. The

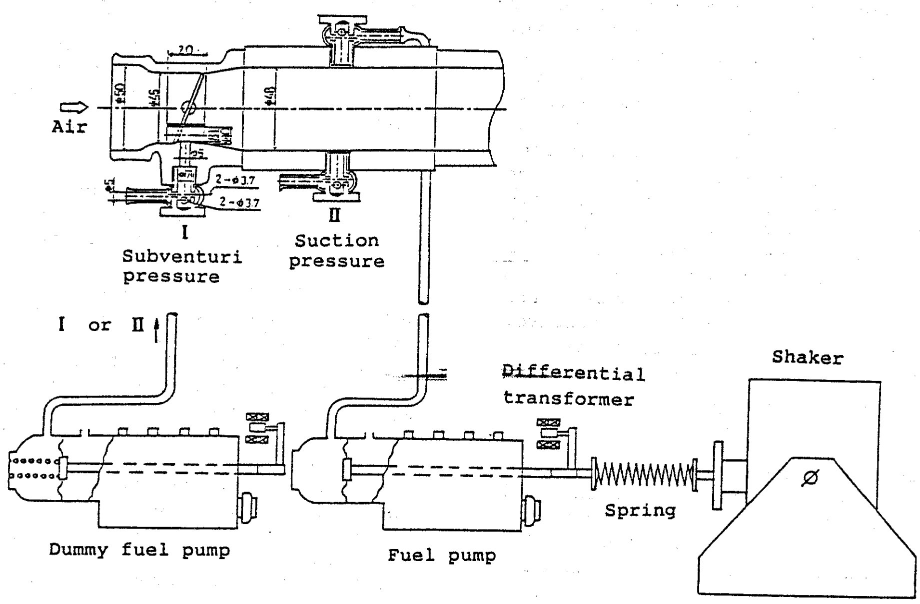

Fig.1 Schematic apparatus of the frequency response.

phase lag of the fundamental frequency component of the engine speed to that of the rack displacement at each engine speed is shown in Fig.5. The phase lag due to engine inertia alone tends to a maximum of

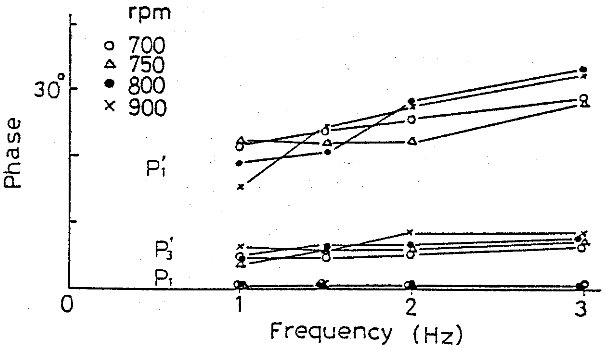

Fig.2 Phase lag of the governing pressure response to the sinusoidal variation of engine speed.

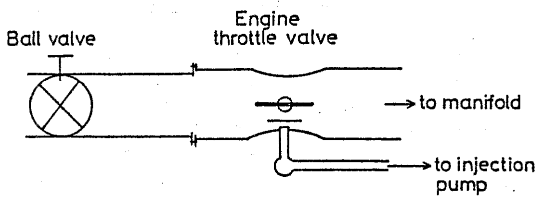

Fig.3 A subventuri beside the throttle valve fully opened and a ball valve added as an adjustable throttle for pneumatic speed control.

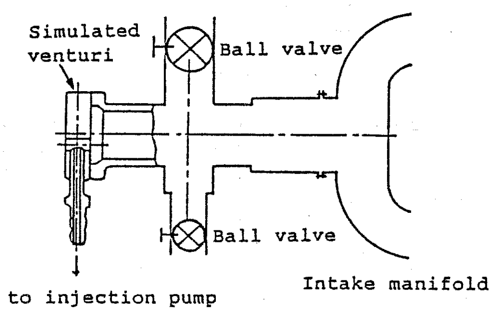

Fig.4 A simulated subventuri combined with two ball valves attached to the intake manifold instead of the throttle valve-subventuri assembly.

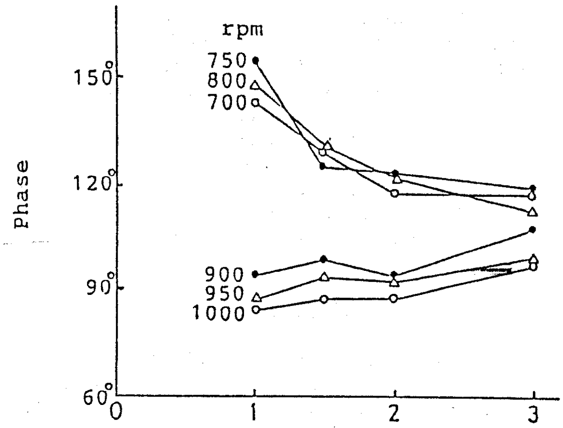

Fig.5 Phase lag of the engine speed response to the sinusoidal variation of fuel rack displacement.

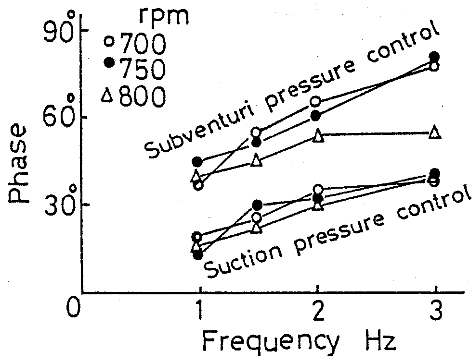

Fig.6 Phase lags of the rack displacement response to the sinusoidal variation of engine speed.

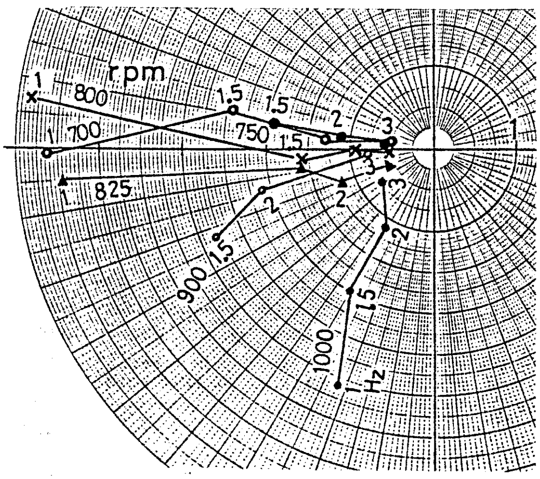

Fig.7 Nyquist diagram for the open loop system under the subventuri pressure control.

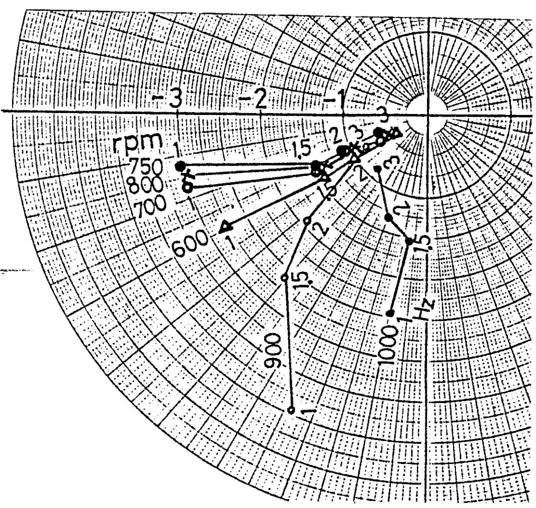

Fig.8 Nyquist diagram for the open loop system under the suction pressure control.

90° ; accordingly the additional lag may be accounted for by assuming that there is a delay between rack displacement, fuel injection and torque.

3.3 Frequency characteristics of the pneumatic governor system

The phase lags of the control rack displacement relative to the engine speed fluctuation are shown in Fig.6, on both cases where the governing pressure is taken at the subventuri beside the throttle valve or taken at the common intake duct just down the subventuri. The phase lags are 53～64° and 29～35° under the subventuri pressure control and under the suction pressure control respectively, at an engine speed fluctuation of 2 Hz : the phase difference between them is about 25°. The phase lag of subventuri pressure, as stated previously in Fig.2, is 25～30° at 2 Hz, whereas that of suction pressure is 6～7° : the phase difference between them is 20～25° , which means that the result of Fig.2 and that of Fig.6 are in good agreement.

3.4 Stability discrimination of the closed loop based on the frequency characteristics of the open loop

Now we consider an open loop of subventuri pressure control with a series connection between rack displacement of the fuel pump, fuel injection, combustion, torque, subventuri pressure and rack displacement of the dummy pump. In Fig.7 is shown the Nyquist diagram where the amplitude and phase characteristics of the rack displacement of the dummy pump vs. the fluctuation of the fuel pump are plotted in the complex plane for frequencies. The argument from the positive real axis and the magnitude indicate the phase angle and the ratio of the amplitudes respectively. In the range of engine speeds from 700 to 800 rpm, amplitude ratio and phase angle for a frequency of 2 Hz are approximately unity and -180° respectively. Since the governor is inherently designed to reverse the effect of an increase or decrease of engine speed, accordingly it causes another phase lag of 180° . Thus, when an oscillation of 2 Hz as an input signal is given at the entrance of the open loop, the output signal has the same amplitude as the input signal and has a phase lag of 360°, which means that a steady hunting of 2 Hz occurs when the open loop is closed(4). Further, there is a phase shift oscillator in the electronic field ; an oscillator can be formed by inserting a phase shifter in a closed loop amplifier.

In Fig.8 is shown a Nyquist diagram for the open loop of suction pressure control where the subventuri pressure is displaced by the suction pressure.

From Fig.7 and Fig.8, it is seen that the system is unstable in the range from 700 to 800 rpm and stable in the range from 900 to 1000 rpm under the subventuri pressure control, whereas the system tends to be more stable and no hunting occurs even in the range from 700 to 800 rpm under the suction pressure control. These results agree well with the actual phenomena.

In Fig.9 are shown the variations of the rack displacement of the fuel pump supplied with the subventuri pressure and the suction pressure respectively vs the engine speed variation with a frequency of 2 Hz at 800 rpm.

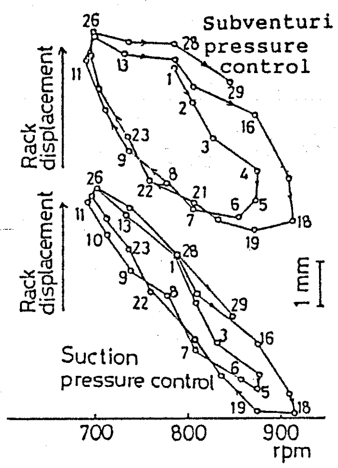

Fig.9 Phase-plane representation of fuel rack displacements to sinusoidal engine speed (measured).

4. Conclusions

To reveal the mechanism of the low speed hunting, the closed engine-governor loop was divided into two open loop systems : an engine system through which the engine speed responds to the displacement of the fuel control rack and a pneumatic governor system with a dummy pump through which vice versa. The frequency responses of the two open systems were measured on the tested engine without hunting under suction pressure control with its pump control rack given a low frequency harmonic excitation by a shaker through the rack spring.

The stability criteria of the closed engine-governor loop showed that there exists a hunting, i.e., a limit cycle of a nonlinear system under the subventuri pressure control. Further, no hunting occurs under the suction pressure control because the phase lag of the governing pressure is minimized.

In the 3rd report, computer simulation of the low speed hunting will be described.

Acknowledgements

The author is grateful to Professor K.Tsuda of the Faculty of Engineering, Yokohama National University, Professor H.sakai and Mr. Y.Ohtake of the Faculty of Engineering, University of Tokyo for their suggestions and encouragements throughout this study.

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