Bulletin of JSME, Vol. 28, No. 243, September 1985

Paper No. 84—0244

Low Speed Hunting of the Pneumatically Governed Compression-Ignition Engine*

(1st Report, Various Experiments for Identifying the Cause)

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The purpose of this study is to reveal the mechanism of the low speed hunting peculiar to the pneumatically governed engine, and to work out its preventive measure. In the present report, it is first shown that the conventional linear theory on the engine-governor system does not explain the actual phenomena. Further, on the basis of the experimental investigation it is found that the key factor is the phase lag of the governing pressure taken at a narrow 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 inlet duct just down the throttle valve and the subventuri.

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

1. Introduction

At the present stage of development of the compression-ignition engine, its smooth running over all speed range is not yet realized; particularly on a pneumatically governed compression-ignition engine the idling engine speed is hardly kept constant, and consequently a low frequency noise of its own is generated. This fluctuation of the engine speed is called low speed hunting. A pneumatic governor controls the fuel delivery by displacing the fuel control rack with the reduced pressure taken at a narrow passage called subventuri beside a throttle valve.

Many studies on the governing and transient characteristics of engines have been carried out in the past 30 years (1) ~ (19). As for hunting in actual systems, however, there have been few studies(20) ~(23); further, these studies do not give a sufficient explanation for these phenomena. Welbourn et al.(20) investigated the behaviors of closed loops on the basis of the frequency characteristics of both mechanical governor and hydraulic governor. A remarkable feature of their work is consideration of phase lag of each element, and they point out that there exists a phase lag between the control rack displacement and the developed torque. However the calculated results do not agree with the experimental ones of the actual system, though the reason of disagreement has been explained to be due to a non-viscous damping of the governor. No more investigations have been carried out. Kaneko (21) has studied on the stability limit of a linear system with a mechanically governed engine using the Hurwitz criterion; but, the definition of the stability limit of the actual system is not clear and there is not enough correspondence between the theory and the specifications and constants of the actual system. Fujihira (22) and Ishimaru(23) have measured characteristic values of engine, fuel pump and pneumatic governor, and they have found out the hunting range on the basis of the stability criterion of a small oscillation with pneumatically governed engines (1)(24)(25)(26). Nevertheless, there yet remain the questions about the measuring method of damping coefficient of the pneumatic governor system in their works. Further, these studies only present the stability around the equilibrium point, accordingly it is impossible to predict whether the oscillation with a large amplitude would occur or not. In addition, the frequency of oscillation based upon the theory of small osillations differs from that in reality.

The purpose of the present study is to reveal the mechanism of the low speed hunting peculiar to the pneumatically governed four-storoke engine with 4 cylinders, and to work out its preventive measure. In this report, it will firstly be shown that the conventional linear theory on the engine-governor system based on the derived equation of motion of the pneumatic governor system(27) does not explain the actual phenomena; further, various experiments for identifying the cause of low speed hunting are described.

* Received 28th May,1984.

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2. Outline of Engine Governing System and Low Speed Hunting Phenomena

A Bosch-type individual fuel injection pump with its control rack locked delivers an increased quantity of fuel in each injection with an increased engine speed except in high speed running ; thus the engine torque also increases with an increasing engine speed, so that the equilibrium of the idling speed is statically unstable. To get rid of this, a governor is additionally provided. Reduced pressure taken at the subventuri caused by increased engine speed is applied to displace the control rack in the direction of decreasing fuel delivery through a diaphragm combined with a spring. The engine speed depends on the throttle valve opening.

In Fig.1 is shown an example of recorded hunting behavior of the pneumatically governed four-stroke engine (4 cylinders, swirl-chamber type, 1986 cm^3, idling at 800 rpm), where P_v, P_d and X are subventuri pressure, diaphragm chamber pressure and fuel control rack displacement respectively. The engine hunts with a frequency of about 2 Hz. The control rack moves to and fro with a large amplitude approaching the maximum stroke of 8.5 mm, while the motion comprises a component of the hunting frequency and a component of a higher frequency caused by the suction process of each piston. Since the natural frequency of the pneumatic governor system of 4.5 Hz(27) is lower than the frequency of the variation of suction pressure, the phase of the higher frequency component of the control rack displacement is reverse to that of the reduced pressure. The mean engine speed for each 180° crank angle swings up and down in the speed range between 650 and 990 rpm, and the pressure of both subventuri and diaphragm chamber decreases with an increased engine speed, forcing the control rack in the direction of reducing the fuel delivery; particularly the pressure curve of the diaphragm chamber shows some plus value larger than the atmospheric, indicating a dynamic effect of the system consisting of a liaison pipe and a chamber of reduced pressure. With the engine tested, the so-called low speed hunting occurs in the range of mean engine speed from 650 rpm to 850 rpm. The maximum amplitude and period of hunting are 150 rpm and 0.5 s respectively. Figure 2 shows the amplitudes of engine speed variation versus mean speed.

3. Discrepancy between the Conventional Hunting Theory and the Actual Phenomenon.

To discriminate the occurence of huntings, the Routh-Hurwitz stability criterion has been applied to the characteristic equation of the linear system. Equation(1) is a differential equation of a closed system derived from the equation of motion of the engine, the relation of the developed torque to the fuel delivered per stroke, the equation of motion of the pump rack, and the characteristics of pressure reduction at the subventuri.

$$m_e J\frac{d^3n}{dt^3}+\left[-m_e\left(\frac{\partial T_e}{\partial N_e}\right)_0+C_eJ\right]\frac{d^2n}{dt^2}+\left[-C_e\left(\frac{\partial T_e}{\partial N_e}\right)_0+kJ\right]\frac{dn}{dt}+\left[-k\left(\frac{\partial T_e}{\partial N_e}\right)_0-A_d\left(\frac{\partial P}{\partial N_e}\right)_0\left(\frac{\partial T_e}{\partial X}\right)_0\right]n=0 \quad \cdots\cdots(1)$$

where,

$J=2\pi I/60$

I :equivarent inertia of engine

N_e, n :engine speed rpm , variation

T_e, τ :shaft torque , variation

m_e :effective mass of the moving parts of the pneumatic governor system

C_e :equivalent viscous damping coefficient for the pneumatic governor system

k :stiffness of the rack spring

A_d :effective diaphragm area

P, p :reduced pressure at the subventuri, variation

X, x :fuel rack displacement , variation

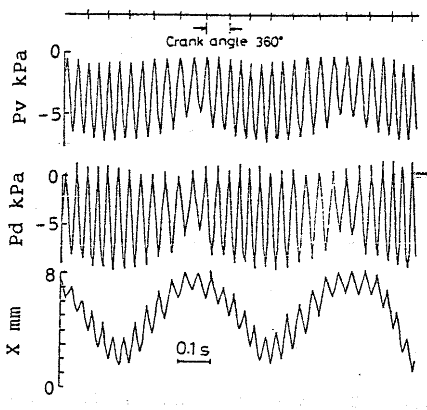

Fig.1 An example of recorded hunting behavior (800 rpm).

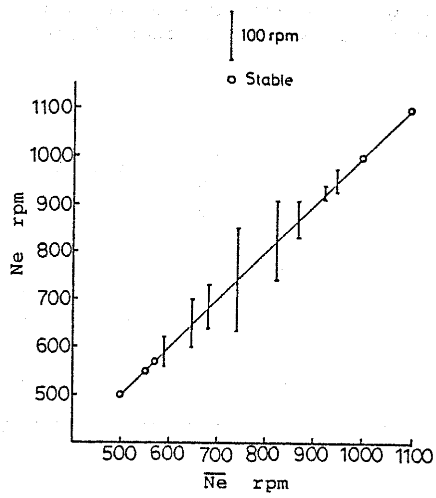

Fig.2 Amplitudes of engine speed variation.

Subscript
0:equilibrium point

The condition required for stability is given by Eq.(2),

$$\left[-m_e\left(\frac{\partial T_e}{\partial N_e}\right)_0+C_eJ\right]\left[-C_e\left(\frac{\partial T_e}{\partial N_e}\right)_0+kJ\right] > m_eJ\left[-k\left(\frac{\partial T_e}{\partial N_e}\right)_0-A_d\left(\frac{\partial P}{\partial N_e}\right)_0\left(\frac{\partial T_e}{\partial X}\right)_0\right] \quad \cdots\cdots\cdots\cdots(2)$$

The measured hunting region and the calculated results for several rack spring sfiffnesses are shown in Fig.3, where the liaison pipe of the pneumatic governor is 40 cm long and has an internal diameter of 8 mm. The constants of the pneumatic governor are as follows: effective mass m_e =0.273 kg, standard rack spring stiffness k_0 =204 N/m, equivarent damping coefficient C_e =24.9 Ns/m, effective diaphragm area A_d =21.0 cm (27). The value of the equivalent engine inertia I is 0.261 kg m^2. In Table 1 are given the constants relating the developed torque to the engine speed $(\partial T_e/\partial N_e)_0$, that to the rack displacement $(\partial T_e/\partial X)_0$, and the subventuri depression to the engine speed $(\partial P/\partial N_e)_0$, for each desired engine speed around the no load. The agreement between the experimental and calculated results is not good. In Fig.4 are shown the measured hunting frequency, the natural frequency of the governed engine calculated from Eq.(1) and the calculated natural frequency of the pneumatic governor. The calculated frequency of a linear system is higher than the measured, being rather close to the frequency of the pneumatic governor system. Figure 5 shows the calculated results about the transient behavior of the linear system when the desired engine speed is 800 rpm and the stiffness of the rack spring is k_0 . When an initial engine speed deviation of 10 rpm is given, it gradually develops into an oscillation with a frequency of 4.1 Hz. The divergence of the actual system is produced like Fig.6; as the throttle valve is opened further from the low speed running, a small hunting appears, and accordingly the amplitude of variation of subventuri pressure P_v, that of pressure in the diaphragm chamber P_d , that of fuel rack displacement R_e , and that of engine speed N_e increase. The frequency of oscillation is near 2 Hz.

4. Various Experiments for Identifying the Cause of Low Speed Hunting

4.1 Various experiments for identifying the cause (1)

From the forms of recorded torque applied to the flywheel from the crank shaft, engine speed and fuel rack displacement when hunting occurs, it is verified that the amplitude of the torque wave with higher engine speed is larger than that with lower engine speed when those two values of rack displacemant during the fuel injection period are almost the same. Further, by removing an injection nozzle from one of the four cylinders and injecting fuel into the air, the injection momentum measured with a pressure indicater, the crank angle, rack displacement and engine speed were recorded in order to investigate the rack displacement during the injection period. Hunting still occurs under the combustion of the remaining three cylinders, and at a

table 1 The data for the calculation

N_e	$-(\partial T_e/\partial N_e)_0$	$(\partial T_e/\partial X)_0$	$-(\partial P/\partial N_e)_0$
rpm	N·m·s	(N·m)/cm	(N/cm²)/rpm
500	−3.48	161	6.67×10^{-4}
600	−1.47	166	6.63×10^{-4}
700	−2.65	304	6.21×10^{-4}
800	−1.76	265	5.58×10^{-4}
900	0.78	294	4.85×10^{-4}
1000	0.59	88	3.59×10^{-4}
1100	0.59	113	3.41×10^{-4}

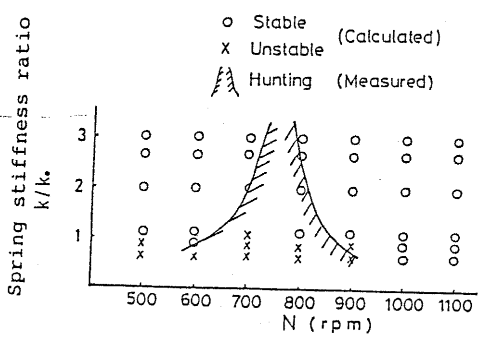

Fig.3 The measured hunting range and the calculated one (conventional theory).

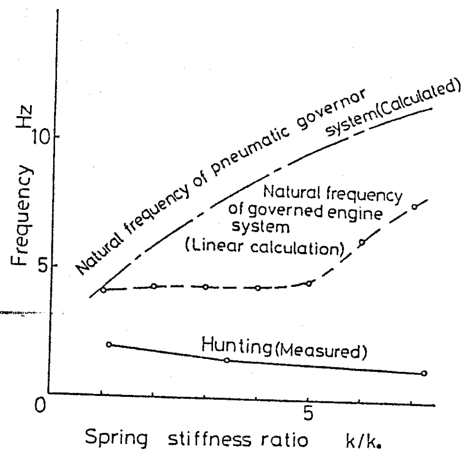

Fig.4 The measured hunting frequency, calculated frequency of governed engine and calculated frequency of pneumatic governor.

mean engine speed of 850 rpm, the mean engine speed for each 180° crank angle fluctuates in the speed range between 730 and 1030 rpm with a period of 0.5 s. It is confirmed that injection momentum depends not only on the rack displacement but also on engine speed, and that fuel is sprayed near the minimum of the higher frequency component of the rack displacement.

There was no phase difference between crank shaft and cam shaft of fuel injection pump in the range of lower engine speeds under 1200 rpm, which means that the automatic timer does not affect the phenomena.

For the purpose of examining whether or not the resonance of intake system is related to the phenomena, the engine was operated with insertion of a straight pipe with 47.6 mm internal diameter and 565 mm length between the venturi and the intake manifold; but the hunting phenomenon did not change.

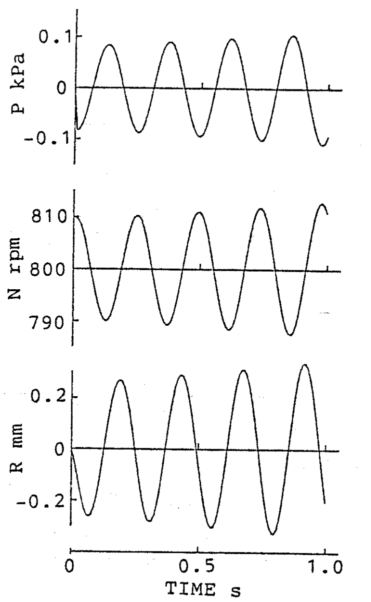

Fig.5 The calculated divergence of the linear system from the equilibrium point 800 rpm

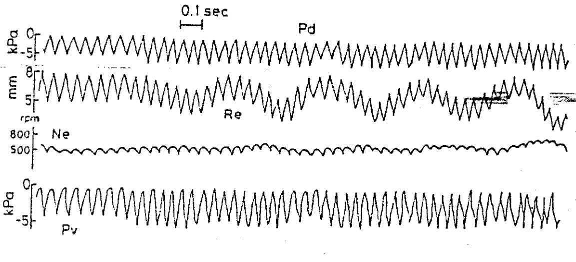

Fig.6 The divergence of hunting in the actual system.

4.2 Various experiments for identifying the cause (2)

4.2.1 Disappearance of hunting due to suction pressure control.

The suction pressure was taken out from the tap II attached to the straight pipe with 48 mm internal diameter and 101 mm length inserted between the venturi and the end of intake manifold shown in Fig.7. It was found that the hunting disappears when this suction pressure is substituted for the subventuri pressure to govern the rack displacement of the fuel injection pump. Here we name the methods a subenturi pressure control and a suction pressure control, respectively, when the tap I and the tap II are connected to the chamber of reduced pressure.

Under the subventuri pressure control, engine speed N_e exhibits a long-period oscillation with an amplitude of about 150 rpm and a frequency of 2 Hz at a mean speed of 800 rpm, as described previously. A recorded example of the engine speed and the rack displacement at 800 rpm under the suction pressure control is given in Fig.8, showing stable running without a low frequency oscillation. In the above figure, the higher frequency components are variations caused by the suction stroke of each piston.

4.2.2 Comparison in the engine running between the subventuri pressure control and the suction pressure control.

In Fig.9 are shown the variations under the suction pressure control on the phase plane of the mean engine speed for each 180° crank angle N_x and the rack displacement during the fuel injection at each engine speed. Low frequency oscillation does not occur. The variations under the subventuri pressure control are shown in Fig.10. A response of the system, when removing the hand from the rack after reducing the engine speed from 800 rpm to about 600 rpm by moving the rack manually in the direction of decreasing the fuel quantity, is shown in Fig.11; the trajectory converges to the equilibrium state of 800 rpm rapidly with a disturbance of significantly large magnitude.

4.2.3 Comparison between the variation of subventuri pressere and that of suction pressure

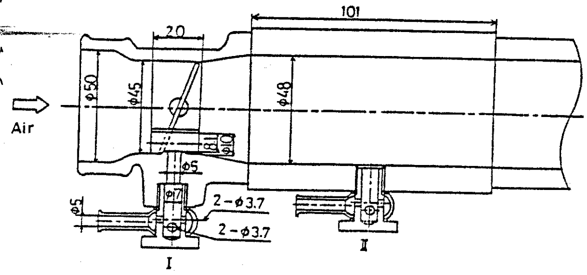

Fig.7 The structure of pressure control units.

The comparison between the subventuri pressure and the suction pressure was made to investigate the difference in dynamic characteristics between the two. When connecting the liaison pipe from the tap shown in Fig.7 to the dummy injection pump added, the two pressures above in the diaphragm chambers under the low frequency oscillatoin of engine speed are shown in Fig.12. When the amplitude and period of oscillation are about 120 rpm and 0.5 s, respectively, at 800 rpm, the minimum of the reduced pressure in the chamber of the engine-fuel-pump P_{4e} lags to the maximum speed of N_π of 948 rpm, whereas, that of dummy pump P_{4d} does not lag. Figure 13 shows records of the rack displacemant R_e of engine fuel pump and R_d of dummy fuel pump when there is a variation of speed with a period of 0.5 s at 750 rpm; the minimum of R_e lags more than that of R_d to the maximum speed of N_π .

Suction pressure P_3 which is not connected to the chamber of reduced pressure does not lag. It was confirmed that there is no phase lag with the outputs of differential transformers for measuring the rack displacements, and the rack displacement of the engine-fuel-pump

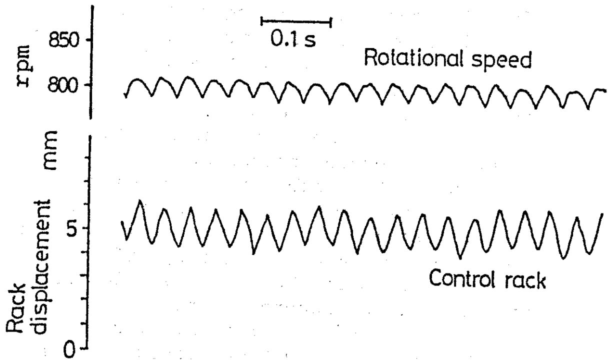

Fig.8 Running under the suction pressure control (800 rpm)

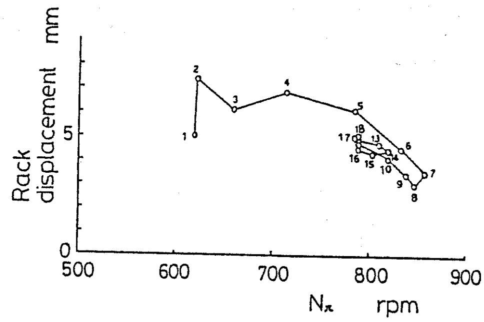

Fig.11 A transient response of the system under the suction pressure control.

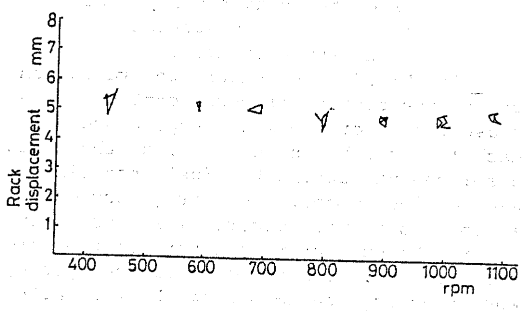

Fig.9 The variations under the suction pressure control on the phase plane of engine speed and the rack displacement.

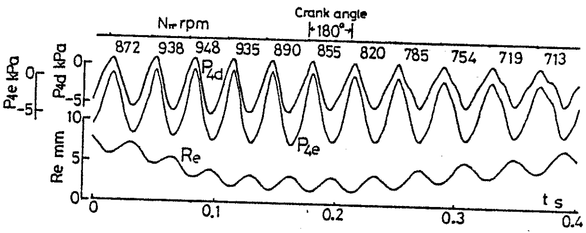

Fig.12 The comparison between the subventuri pressure and the suction pressure in the chambers of reduced pressure.

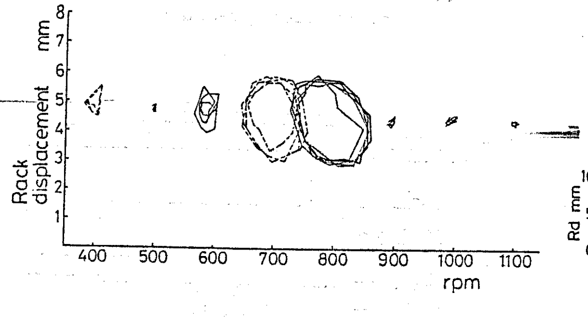

Fig.10 The variations under the subventuri pressure control on the phase plane of engine speed and the rack displacement.

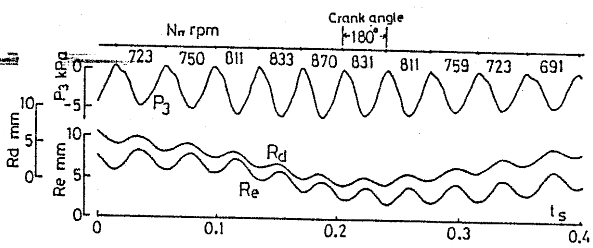

Fig.13 The comparison between the fuel racks moved by the subventuri pressure and the suction pressure, respectively.

equals that of the dummy-pump when the values of those two diaphragm-chamber pressure are the same.

In order to compare the subventuri pressure with the suction pressure, the phase differences between them were investigated under the low frequency oscillation of engine speed; when the low frequency displacement equivalent to the hunting amplitude was given to the end of the rack spring fixed to a shaker under the suction pressure control, the responses of the subventuri pressure and the suction pressure to the low frequency oscillation of engine speed were recorded, respectively, and the phase differences were examined with a digital analyzer. There is no difference between the above two when the detected pressure is not connected to the chamber of reduced pressure of the dummy pump, whereas the phase shift of low frequency oscillation of subventuri pressure to that of suction pressure is from 20 to 25 degrees when connected to it.

5. Conclusions

The main results are summarized as follows:

(1) The conventional linear theory on the engine-governor system does not explain the actual phenomena; the calculated hunting range and hunting frequency do not agree with the experimental results.

(2) The motion of the fuel control rack when a hunting occurs comprises a component of the hunting frequency and a component of a higher frequency caused by the suction stroke of each piston.

(3) It was found that there is a phase lag in the governing pressure taken at a narrow passage called subventuri beside a throttle valve, which is the key factor, because the hunting disappears when the phase lag is minimized by displacing the pressure source to the common inlet duct just down the throttle valve and the subventuri.

In the 2nd report, the frequency responses of the engine system and the pneumatic governor system composing a closed loop will be determined experimentally, and the occurence of a hunting under the subventuri pressure control and non-existence of it under the suction pressure control will be verified.

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, and Professor Y.Nagano of Nagoya Institute of Technology for their suggestions and encouragements throughout this study.

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