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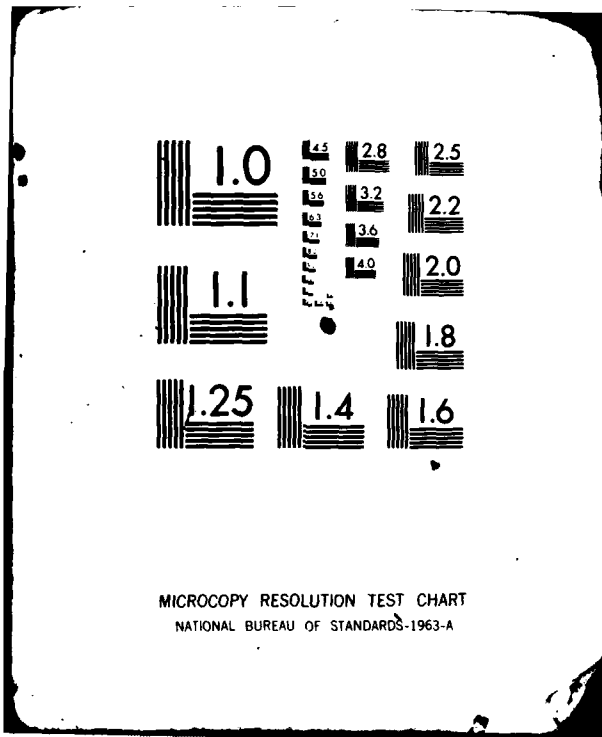
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THE ANALYSIS FOR REGULATION PERFORMANCE
OF A VARIABLE THRUST ROCKET ENGINE
CONTROL SYSTEM

by

Zhou Xiwen



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Abstract

In this paper, the constituent, operation principle and regulation process of the bipropellant variable thrust rocket engine for a variable area injector that uses a solenoid valve control are introduced.

According to the constituent and practical operation process of such an engine control system, the mathematical models for the main links are given, by transfer function method, the dynamic and steady-state performance is analysed, according to the calculation results, the effect on dynamic performance and steady error for the engine control system is further described.

I.

THE CONSTITUENT AND OPERATION PRINCIPLE OF THE ENGINE CONTROL SYSTEM

In this text we want to introduce the use of a pilot circuit that possesses a specific frequency and can vary pulsewidth, controlling two high performance solenoid valves, passing through liquid flow rate variations to change the pressure in the hydraulic pressure cavity, making the injector needle valve move up and down to change the injector circulation cross section, control the propellant flow rate variations, and bring about thrust variations. The control system is primarily composed of the pilot circuit, the solenoid valve, and the thrust chamber that possesses the variable cross section injector. Their interrelation is shown in Fig. 1.

The pilot circuit is composed of the operational amplifier, the pulse oscillator, the resonant delay oscillator, and a solenoid valve drive circuit. The operational amplifier conducts alternate operations through the control voltage signal and the combustion chamber pressure feedback signal, and sends out a voltage deviation signal. The pulse oscillator sends out a voltage pulse signal of a specific frequency and width, and goes to control the resonant delay oscillator. The resonant delay oscillator conducts the variable width pulse operations that restrain the frequency of the pulse oscillator and the operational amplifier to export the degree of

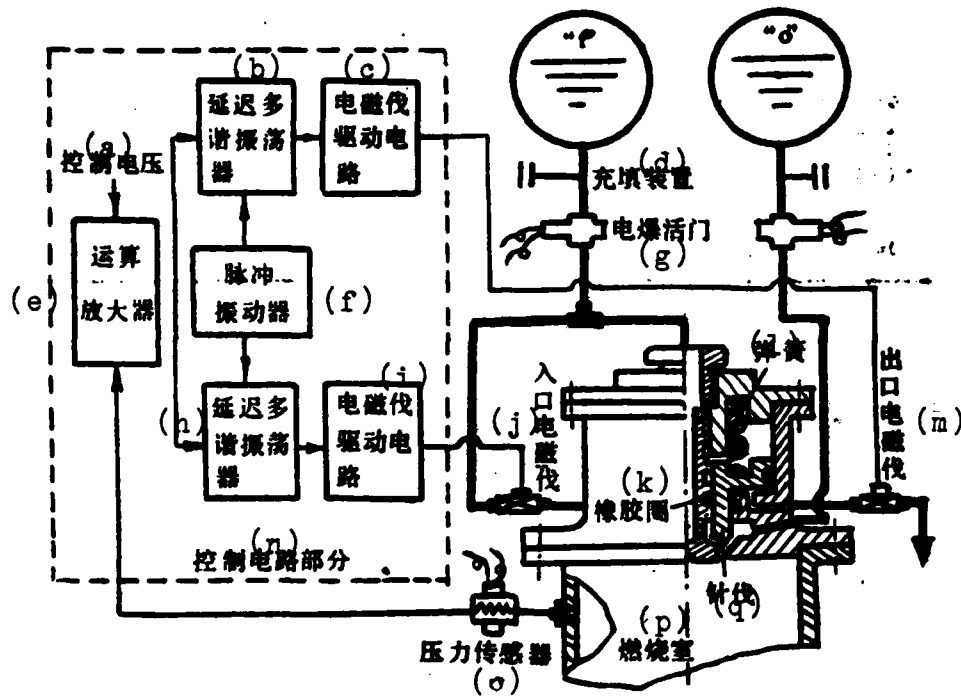


Fig. 1. DIAGRAM OF THE OPERATION PRINCIPLE OF THE ENGINE
 Key: (a) Control voltage; (b) Resonant delay oscillator; (c) Solenoid valve drive circuit; (d) Filling mechanism; (e) Operational amplifier; (f) Pulse Vibrator; (g) Electro-ignitor; (h) Resonant delay oscillator; (i) Solenoid valve drive circuit; (j) Solenoid valve intake; (k) Rubber gasket; (l) Spring; (m) Solenoid valve escape; (n) Pilot circuit section; (o) Pressure capsule; (p) Combustion chamber; (q) Valve needle.

voltage deviation to control it. This variable pulse signal of a certain frequency goes through the solenoid valve drive circuit to carry out amplification, and spur on solenoid valve pulse operations.

The two solenoid valves and the injector hydraulic pressure cavity are linked together. When the deviation signal of the pilot circuit makes a positive voltage signal, it controls the solenoid valve intake operations. Pressure rises in the hydraulic pressure chamber, and pushes the injector needle valve to rise. The injector cross section expands, the propellant flow rate increases, and the thrust rises. Conversely, when the deviation signal of the pilot circuit makes a negative voltage signal, it controls the solenoid valve escape operations, ejects the liquid in the hydraulic pressure cavity, and causes the pressure in the hydraulic pressure to drop. The injector needle valve is under the effect of the

spring force, the injection flow area reduces, the propellant flow rate reduces, and the thrust reduces.

The control operation of the injector needle valve uses a combustible, goes through the intake solenoid valve to enter the hydraulic pressure chamber. Because the controlling liquid flow rate is very small, it goes through the exhaust solenoid valve and directly ejects into the atmosphere. A system can also be designed that makes the controlling fluid return to the combustible.

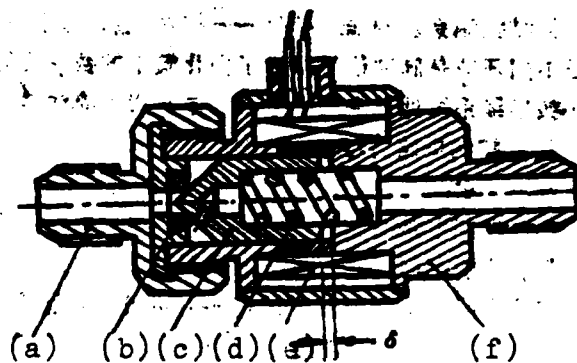


Fig. 2. STRUCTURAL DIAGRAM OF THE SOLENOID VALVE
 Key: (a) Escape orifice; (b) Needle valve seat; (c) Needle valve;
 (d) Spring; (e) Coil; (f) Intake orifice.

Thus it can be seen that this kind of variable thrust rocket engine system changes the size of the injector flow cross section to change the propellant flow rate, and obtain the objective of thrust control. The engine propellant supply system does not conduct regulation. The characteristics of its program are that the control system is simple, the operation is dependable, but the regulation precision isn't high enough.

The pilot circuit's operational parameter is as follows:

- voltage of the pilot circuit's power supply $V = 28$ [V]
- controlling voltage of the circuit $V_c = 0 \sim 5$ [V]
- pulse oscillator operational frequency $f = 50 \sim 100$ [Hz]
- Escape voltage of the feedback pressure capsule $V_f = 0 \sim -5$ [V]
- Escape voltage of the operational amplifier
 $V_A = 0.1 \sim 1.1 \sim 2.1$ [V]

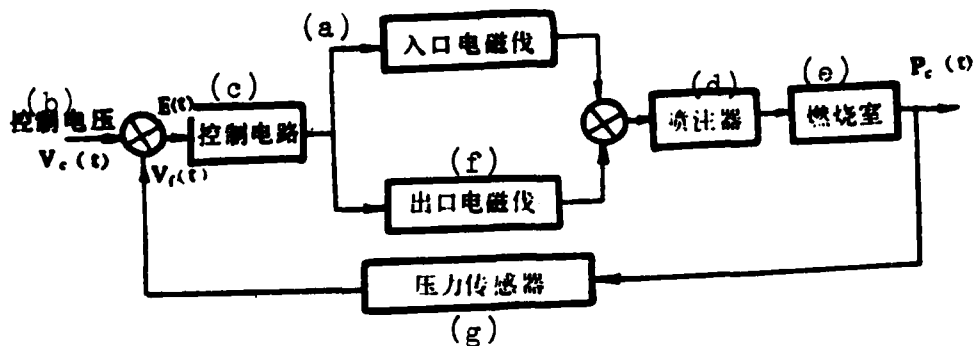


Fig. 3. DIAGRAM OF THE CONTROL SYSTEM

Key:(a) Intake solenoid valve; (b) Control voltage; (c) Control circuit; (d) Injector; (e) Combustion chamber; (f) Exhaust solenoid valve; (g) Pressure capsule.

II.

MATHEMATIC EQUATIONS FOR THE MAIN LINKS OF THE CONTROL SYSTEM

The solenoid valve of the control system is controlled by the pilot circuit, and conducts variable width pulse operations. Therefore, a mathematical model of the pilot circuit and solenoid valve can be established. In the mathematical treatment process we must encounter the nonconsecutive alternate system, and approach the problem of the Z alternate.

But the input signal of the control system-control voltage V_c , and the output signal-thrust chamber pressure P_c are consecutive signals, only the middle links are pulse signals. In order to simplify the overelaborate mathematical deductions, we can build the mathematical models of the main links of the circuit, solenoid valve, injector, combustion chamber, etc. based on the actual operations of the engine system and the regulation conditions, in accordance with consecutive system mathematical treatments.

1. Equation for the Pilot Circuit

Basic Assumptions:

1) The pulse operation frequency of the pilot circuit is specific. The size of the circuit operational frequency influences the dynamic

state of the engine system and the steady-state performance. Moreover, the size of the frequency receives influence from the performance of the solenoid valve itself.

Regarding the explanation of the engine system, experiments show clearly that its operational frequency can choose within the scope of 50-100 Hz.

2) The pulsewidth of the pilot circuit is in a direct ratio with the voltage deviation (control voltage and feedback voltage differences-deviation signal). (Experiments prove the variations of pulsewidth in direct ratio with basic voltage deviation.)

In order to enhance the dynamic state performance and the steady state performance of the engine system, the pulsewidth should adjust as wide as possible. The pulse frequency and pulsewidth of the pilot circuit do not affect each other, and can be separated from regulation.

3) The duration of the starting forward edge of the solenoid valve is specific. Because the solenoid valve is an inductive element, the solenoid force must overcome the friction, the spring force, the damper force, and the hydraulic pressure of the needle valve. The solenoid force is in direct ratio with the amount of current. The current rises to the duration variations in accordance with the index curve. Therefore it forms the forward edge when the solenoid valve is open. The curve of a solenoid valve operational current shown in Fig. 4 expresses

The starting forward edge $\tau_0 = 3-5\text{ms}$

The needle valve opening period $\tau_1 = 0.5\text{ms}$

τ_0 represents one effective pulsewidth of the solenoid valve pulse. To increase the pulsewidth actually is to increase the effective pulsewidth.

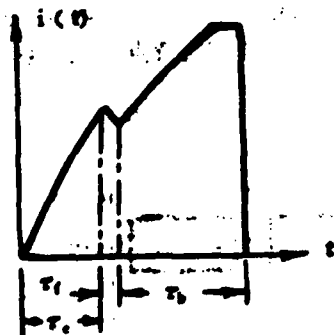


Fig. 4. CURVE OF A SOLENOID VALVE OPERATIONAL CURRENT

On the basis of the above analysis, we can express the equation for the circuit-solenoid valve:

$$K_b = \frac{\tau_b}{E_0} \quad (1)$$

Where K_b is circuit gain

[S/V]

$E_0 = V_c - V_f$ Differences of control voltage and feedback voltage [V]

When $V_f = 0$, $E_0 = V_c$

τ_b is effective pulsewidth [S]

When engine regulation arrives at operational conditions, after pulse frequency is chosen, the pulsewidth regulation is the widest, K_b also then is set. For example, $f = 50\text{Hz}$, $E_0 = V_c = 5\text{V}$, to the pulsewidth that should be the largest, $\tau_a + \tau_b = 20\text{ms}$, ($\tau_a = 5\text{ms}$, $\tau_b = 15\text{ms}$, omit τ'), then $K_b = \tau_b / E_0 = 3 \times 10^{-3} \text{ [S/V]}$.

The equation for the pulsewidth of the solenoid valve is:

$$b(t) = k_b \cdot E(t) \quad (2)$$

The effective operational duration that is within the duration of the solenoid valve unit is called the effective pulse operational coefficient of the solenoid valve, using $\eta(t)$ to express clearly:

$$\eta(t) = fb(t) \quad (3)$$

Where f is the pulse operational frequency of the solenoid valve [Hz]

$\eta(t)$ is the effective pulse operation coefficient ($\eta(t) < 1$)

2. Equation for the Flow Rate of the Solenoid Valve

Basic Assumptions:

1) After the solenoid valve goes through the forward edge interval within the pulse operation period, the needle valve opens instantaneously. Because after the solenoid valve goes through the forward edge interval $\tau_a = 3\sim 5\text{ms}$, the duration that the needle valve is open is only $\tau = 0.5\text{ms}$, $\tau \ll \tau_b$, hence τ' can be dismissed.

2) Experiments show that the closing time of the solenoid valve needle valve-the back edge lessens to 0.5ms, can be omitted, and deems the needle valve to close instantaneously.

On the basis of the preceding assumptions, considering the structure and dimensions of the solenoid valve. We can list the equation for the flow rate of the intake solenoid valve and the exhaust solenoid valve.

The equation for the flow rate of the intake solenoid valve:

$$Q_i(t) = \mu A \sqrt{\frac{2g}{\gamma} [p_o - p_H(t)]}$$

Where μ is the flow rate coefficient

A is the circulation cross section of the solenoid valve

By the calculation of geometric dimensions of the solenoid valve (reference material [2]),

$$A = 2.22\delta(D - \delta/2)$$

δ is the largest interval of the solenoid valve opening

$$\delta = 0.1 \sim 0.4 \text{ mm}$$

D is diameter of the solenoid valve escape orifice [mm]

P_o is hydraulic pressure of the solenoid valve intake orifice [kg/mm²]

$P_H(t)$ is pressure of the main hydraulic pressure cavity of the thrust chamber [kg/mm²]

The equation for the flow rate of the exhaust solenoid valve:

$$Q_e(t) = \mu A \sqrt{\frac{2g}{\gamma} P_H(t)}$$

The liquid of the exhaust solenoid valve will directly enter the atmosphere.

The solenoid valve is pulse operational. Therefore, the actual flow rate of the solenoid valve should lead into the effective pulse operation coefficient $\eta(t)$, and then the equation for the flow rate of the intake solenoid valve and exhaust solenoid valve is

$$Q_i(t) = \eta(t) \mu A \sqrt{\frac{2g}{\gamma} [P_o - P_H(t)]}$$

$$Q_e(t) = \eta(t) \mu A \sqrt{\frac{2g}{\gamma} P_H(t)}$$

Substitute the above equations with $\eta(t)$ and $b(t)$ of equations (2) and (3), and it makes:

$$K_o = f K_b \mu A \sqrt{\frac{2g}{\gamma}} \quad (4)$$

Then the preceding equation for flow rate becomes

$$Q_i(t) = K_o E(t) \sqrt{P_o - P_H(t)}$$

$$Q_e(t) = K_o E(t) \sqrt{P_H(t)}$$

With the preceding principle knowledge of the engine system operations, when there is deviation $E(t) > 0$ of the control voltage and feedback voltage, it controls the intake solenoid valve operations. Conversely, $E(t) < 0$ operates the exhaust solenoid valve. Which one operates depends on whether the deviation signal $E(t)$ is positive or negative.

In order to use an equation for the pilot return circuit to express the equation for the flow rate of the solenoid valve, we must cite two functions. Making

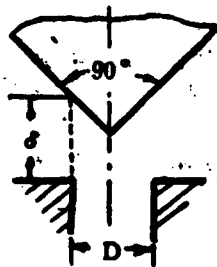


Fig. 5. GEOMETRIC DIMENSIONS OF THE SOLENOID VALVE

$$u(e) = \frac{1}{2|E(t)|} [|E(t)| + E(t)] \quad (5)$$

$$v(e) = \frac{1}{2|E(t)|} [|E(t)| - E(t)] \quad (6)$$

Clearly,

$$\begin{aligned} E(t) > 0, \quad u(e) = 1, \quad v(e) = 0, \\ E(t) < 0, \quad u(e) = 0, \quad v(e) = 1. \end{aligned}$$

Then the equation for the flow rate of the solenoid valve becomes

$$Q_1(t) = K_0 u(e) E(t) \sqrt{P_s - P_H(t)} \quad (7)$$

$$Q_2(t) = K_0 v(e) E(t) \sqrt{P_H(t)} \quad (8)$$

These are two primary non-linear equations. On the basis of applied design requirements of the engine, each time the extent of thrust regulation is comparatively small, thrust regulation variations are a smooth transition. We can use extreme progression to carry out linearization with two equations. As to the intake solenoid valve:

$$Q_1(t) = \frac{\partial Q_1(t)}{\partial E(t)} \Big|_E E(t) + \frac{\partial Q_1(t)}{\partial P_H(t)} \Big|_E \Delta P_H(t)$$

Where

$$\begin{aligned} \frac{\partial Q_1(t)}{\partial E(t)} \Big|_E &= K_0 u(e) \sqrt{P_s - P_H(t)} = K_0 K_1 \\ \frac{\partial Q_1(t)}{\partial P_H(t)} \Big|_E &= K_0 \frac{1}{2} u(e) E(t) [\sqrt{P_s - P_H(t)}]^{-1} = K_0 K_2 \end{aligned}$$

in which

$$K_1 = u(e) \sqrt{P_s - P_H(t)} \quad (9)$$

$$K_2 = \frac{1}{2} u(e) E(t) [\sqrt{P_s - P_H(t)}]^{-1} \quad (10)$$

makes

$$K_1 = K_0 K_2 \quad (11)$$

$$K_2 = K_0 K_1 \quad (12)$$

thus

$$Q_1(t) = K_1 E(t) - K_2 \Delta P_H(t) \quad (13)$$

The same reasoning obtains the equation for the flow rate of the exhaust solenoid valve:

$$Q_2(t) = K_1 E(t) + K_2 \Delta P_H(t) \quad (14)$$

where

$$K_1 = K_0 K_2 \quad (15)$$

$$K_2 = K_0 K_1 \quad (16)$$

$$K_0 = v(s) \sqrt{P_H} \quad (17)$$

$$K_1 = \frac{1}{2} v(s) E_s [\sqrt{P_H}] \quad (18)$$

Equations (13) and (14) can be expressed as one equation:

$$Q(t) = Q_1(t) - Q_2(t) = (K_1 - K_2) E(t) - (K_2 + K_1) \Delta P_H(t)$$

making

$$K_0 = K_1 - K_2$$

$$K_{PH} = K_2 + K_1$$

thus

$$Q(t) = K_0 E(t) - K_{PH} \Delta P_H(t) \quad (19)$$

Clearly, when

$$E(t) > 0, K_0 = K_1, K_{PH} = K_2, Q(t) = \dot{Q}_1(t), \quad E(t) < 0, K_0 = -K_2, K_{PH} = K_1, \\ Q(t) = -\dot{Q}_2(t).$$

The corresponding alternate equation for the flow rate of the solenoid valve is

$$Q(s) = K_0 E(s) - K_{PH} P_H(s) \quad (20)$$

3. Equation for the Main Capsule of the Thrust Chamber

The pressure of the main capsule of the thrust chamber, according to design requirements $P_H(t) < 20 \text{ kg/cm}^2$, and the comparison of common hydraulic pressure systems, the capsule pressure is comparatively low. In the equation for the capsule we don't need to consider the distortion of the capsule housing and the capsule climate due to pressure rising.

Because the spring has preset tension F_0 , when $F_0 = A_H P_{Ho}$, the injector needle valve starts to move. Therefore when $P_H(t) = P_{Ho}$, $y(t) = 0$. Therefore

$$A_H dy(t) = Q(t) dt$$

When $dy(t) > 0$, $Q(t) = Q_1(t)$; $dy(t) < 0$, $Q(t) = Q_2(t)$.

$$y(t) = \frac{1}{A_H} \int Q(t) dt \quad (21)$$

The corresponding alternate formula:

$$Y(s) = \frac{1}{A_H} \cdot \frac{1}{s} Q(s) \quad (22)$$

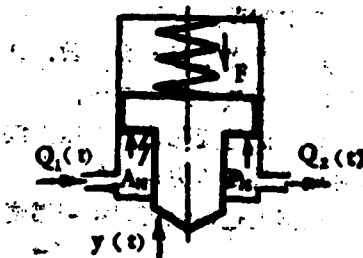


Fig. 6. HYDRAULIC PRESSURE CAPSULE

4. Equation for the Injector Needle Valve Movement

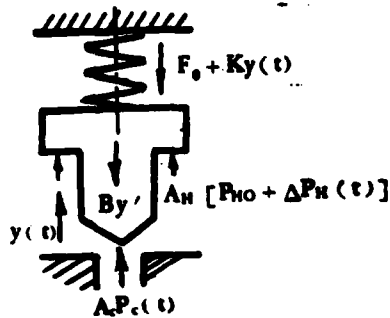


Fig. 7. DIAGRAM OF
INJECTOR NEEDLE VALVE
TENSION

The conditions of the injector needle valve tension as shown in Fig. 7 are expressed:

F_0 - Spring preset tension [kg]

K - Spring rigidity [kg/mm]

$y(t)$ - Needle valve displacement [mm]

$dy(t)/dt$ - Needle valve certain moment of movement speed [mm/s]

P_{H0} - Hydraulic pressure when the needle valve starts to rise [kg/mm²]

$\Delta P_H(t)$ - Hydraulic pressure increments [kg/mm²]

A_H - Hydraulic pressure function area [mm²]

B - Needle valve movement damper coefficient [kg·s/mm]

A_c - Operational area of combustion to the needle valve [mm²]

$P_c(t)$ - Combustion pressure [kg/mm²]

m - Needle valve mass [kg·s²/mm]

The equation for the injector needle valve becomes (reference material [1]):

$$m \frac{d^2 y(t)}{dt^2} + B \frac{dy(t)}{dt} + K y(t) = A_c P_c(t) + A_H \Delta P_H(t) \quad (23)$$

The corresponding alternate formula is:

$$(mS^2 + BS + K)Y(s) = A_c P_c(s) + A_H P_H(s) \quad (24)$$

5. Equation for the Flow Rate of the Injector Needle Valve

$$G_o(t) = \mu_o A_o \sqrt{2g\gamma_o \Delta P_o} \quad \text{oxidant}$$
$$G_f(t) = \mu_f A_f \sqrt{2g\gamma_f \Delta P_f} \quad \text{combustible}$$

Through many experiments it has been proved that when the displacement of the injector needle valve is comparatively small, the changes of flow rate and displacement cause a linear relationship. The two flow rate equations can be expressed as

$$G_o(t) = \psi_o y(t) \quad (25)$$

$$G_f(t) = \psi_f y(t) \quad (26)$$

In the formula the coefficients ψ_o and ψ_f can traverse the experimental determinant of the injector flow rate.

The corresponding alternate formulas for the flow rate equations:

$$G_o(S) = \psi_o Y(S) \quad (27)$$

$$G_f(S) = \psi_f Y(S) \quad (28)$$

6. Equation for the Combustion Chamber

Basic Assumptions:

- 1) Combustion delay τ is constant. Consider that after the propellant is injected into the combustion chamber, it goes through the τ period, and combustible gas is instantaneously produced.
- 2) Combustible gas is the ideal gas.
- 3) The speed of the flow rate variation and the speed of pressure wave propagation are comparable. Consider that the speed of pressure wave propagation is infinitely great, and the pressure in the com-

bustion chamber in any moment or place is even.

On the basis of the above-mentioned assumptions, we can obtain the equation for the combustion chamber (reference material 1)

$$\frac{v_c}{RT_c} \frac{dP_c(t)}{dt} + \frac{A_c}{\beta} P_c(t) = G_o(t-\tau) + G_f(t-\tau) \quad (29)$$

Where v_c - Combustion chamber volume [mm³]

R - Ideal gas constant [mm/^oK]

T_c - Combustible fuel temperature [K]

A_c - Injector nozzle cross section area [mm²]

β - Combustion chamber comprehensive parameter [s]

The corresponding alternate formula :

$$\left(\frac{v_c}{RT_c} s + \frac{A_c}{\beta} \right) P_c(s) = e^{-s\tau} [G_o(s) + G_f(s)] \quad (30)$$

7. Equation for Feedback Pressure Capsule and Circuit Operation Amplifier

The pressure capsule of the engine system being used is a resistance pressure capsule. For this kind of pressure capsule we may consider it an amplify link. Its equation is:

$$V_f(t) = K_f P_c(t) \quad (31)$$

The equation for the circuit operation amplifier is:

$$E(t) = V_o(t) - V_f(t) \quad (32)$$

The corresponding alternate formulas are:

$$V_f(s) = K_f P_c(s) \quad (33)$$

$$E(s) = V_o(s) - V_f(s) \quad (34)$$

III.

TRANSFER FUNCTION OF THE ENGINE CONTROL SYSTEM

To synthesize the preceding equations (20), (22), (24), (27), (28), (30), (33), and (34), the diagram shows the interrelation between several variables.

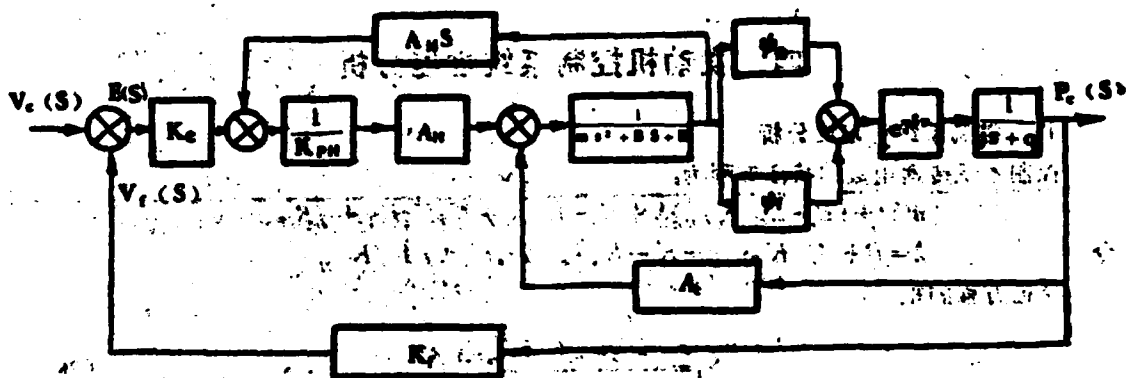


Fig. 8. DIAGRAM OF THE CONTROL SYSTEM

In which $j = v_c / RT_c$, $q = A/B$

Because the engine uses bipropellant spontaneous combustion thrust, ignition delay time τ is comparatively small. General $\tau < 5ms$ can be considered $e^{-\tau s} = 1$.

The volume of a small engine combustion chamber v_c is comparatively small, and the temperature T_c is comparatively high. $RT_c \gg v_c$ can deem $j = v_c / RT_c = 0$.

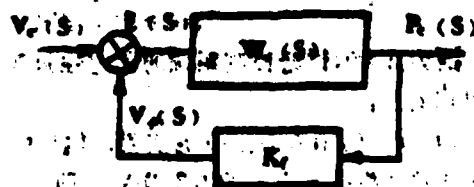


Fig. 9. SIMPLIFIED DIAGRAM

The simplified diagram is the following formula:

$$W(s) = \frac{K_c K_c A_H / K_{P_H}}{ms^2 + (B + A_H / K_{P_H})s + K - K_c A_c} \quad (35)$$

where

$$K_c = \frac{1}{q}(\psi_0 + \psi_f) = \frac{\beta}{A_i}(\psi_0 + \psi_f) \quad (36)$$

K_c represents combustion chamber gain [kg/mm³]

The close link transfer function of the control system:

$$\phi(s) = \frac{K_c K_c A_H / K_{P_H}}{ms^2 + (B + A_H / K_{P_H})s + K - K_c A_c + K_c K_c K_f A_H / K_{P_H}} \quad (37)$$

m -Injector needle valve mass kg s²/mm

B -Injector needle valve damper coefficient kg s/mm

A_H -Needle valve hydraulic pressure operation area mm²

K_{P_H} -Solenoid valve pressure coefficient mm⁵/s kg

K_c -Solenoid valve flow rate gain mm³/s V

K -Spring rigidity kg/mm

K_c -Combustion chamber gain kg/mm³

A_c -Needle valve fuel operation area mm²

K_f -Feedback pressure chamber gain mm²V/kg

When calculating the transfer function, when using $B, P_{Ht}(t=0)$, $P_{Ht} = P_{H0}$ and K_c , according to the actual structure of the engine and the operational parameters, we can use experimental method determinants.

IV.

ANALYSIS OF THE ENGINE CONTROL SYSTEM PERFORMANCE

1. Analysis of Steady State of the Control System

Characteristics of the control system transfer function:

$$mS^2 + (B + A_H/K_{PH})S + K - K_c A_c + K_c K_i K_j A_H/K_{PH} = 0$$

$$\lambda = B + A_H/K_{PH}, \nu = K - K_c A_c + K_c K_i K_j A_H/K_{PH}$$

Root of the characteristic equation:

$$S_1 = \frac{-\lambda + \sqrt{\lambda^2 - 4m\nu}}{2m} \quad (38)$$

$$S_2 = \frac{-\lambda - \sqrt{\lambda^2 - 4m\nu}}{2m} \quad (39)$$

Because $\lambda > 0$, discussing the stability of the control system we only must discuss the root of the characteristic equation, and that is enough. From the root of the characteristic equation S_1 we can see that:

- 1) $\nu < 0$, thus there is the solid root of $S_1 > 0$. The transition weight of output monotonically increases according to the exponential law, and the system is unstable. However, from the plan of the engine control system we can see that if the unstable condition emerges, the pressure in the combustion chamber monotonically increase or monotonically decrease. Because the control system has a closed link system of feedback, the pressure in the combustion chamber exceeds the specific value made to correspond with the solenoid valve operations. This kind of combustion chamber pressure will emerge according to specific frequency and amplitude oscillation model operations. The exhaust and intake solenoid valve alternate operations.
- 2) $\nu > 0$, the solid root of $\lambda^2 - 4m\nu > 0$, $S_1 < 0$, the control system is stable.
- 3) $\nu > 0$, $\lambda^2 - 4m\nu < 0$, S_1 and S_2 both are the conjugate compound radical of the characteristic equation.

In order to further explain that these parameters are the primary influential factors of engine control system performance, we will use the parameters of the engine to conduct actual calculations to add to the explanation.

Primary parameters:

Table 1.

Name	Symbol	Unit	Numerical Value
Injector needle valve mass	m	kg·s ² /mm	1.2x10 ⁻⁵
Needle valve hydraulic pressure operation area	A _H	mm ²	16x10 ²
Needle valve combustible gas operation area	A _c	mm ²	2.5x10 ²
Needle valve damper coefficient	B	kg·s/mm	3.6
Spring rigidity	K	kg/mm	120
Solenoid valve flow area	A	mm ²	0.84
Solenoid valve flow rate coefficient	μ		0.60
Injector needle valve hydraulic pressure	P _{Ht}	kg/mm ²	8x10 ⁻²
Solenoid valve intake pressure	P _c	kg/mm ²	18x10 ⁻²
Solenoid valve pulse operation frequency	f	Hz	80
Pulsewidth	τ	S	6x10 ⁻³
Circuit gain	K _c	S/V	1.2x10 ⁻³
Deviation signal voltage	E _c	V	2
Pressure capsule gain	K _p	V·mm ² /kg	55.56

When experimenting with water as the hydraulic pressure operative, we can calculate the condition of the thrust rise according to the data given in Table 1:

$$K_0 = f K_c \mu A \sqrt{\frac{2g}{\gamma}} = 6.78 \times 10^2 [\text{mm}^2/\text{s} \cdot \text{V} \cdot \text{kg}^{1/2}]$$

$$K_1 = \sqrt{p_c - P_{Ht}} = 0.32 [\text{kg}/\text{mm}^2]^{1/2}$$

$$K_2 = \frac{1}{2} E_c [\sqrt{p_c - P_{Ht}}]^{-1} = 0.32 [\text{V} \cdot \text{mm}/\text{kg}^{1/2}]$$

$$K_3 = K_0 K_1 = 2.17 \times 10^2 [\text{mm}^2/\text{s} \cdot \text{V}]$$

$$K_{pH} = K_0 K_2 = 2.17 \times 10^2 [\text{mm}^2/\text{s} \cdot \text{kg}]$$

If the injector design is good, when the needle valve displaces $h_{\max} < 0.25\text{mm}$, the variations of injector flow rate and needle valve displacement are similar to a linear relationship. The combustion chamber gain K_c can be expressed:

$$K_c = \frac{Pc_{\max}}{h_{\max}}$$

If $Pc_{\max} = 10 \times 10^{-3} \text{kg/mm}^2$, $h_{\max} = 0.25\text{mm}$ thus $K_c = 0.40 \text{kg/mm}^2$.

In accordance with the preceding parameters we are able to calculate the values of the roots v and λ of the characteristic equation, and determine the stability of the engine control system. Moreover, we can see the influence of various parameters on transfer function, and further analyse the primary influential factors of the performance of the engine.

$$\begin{aligned} v &= K - K_c A_c + K_c K_c K_j A_H / K_{PH} = 120 - 100 + 355.58 \times 10^2 = 35.578 \times 10^2 \text{kg/mm} \\ \lambda &= B + A_H^2 / K_{PH} = 3.6 + 11.797 \times 10^2 = 11.83 \times 10^2 \text{kg} \cdot \text{s/mm} \\ \lambda^2 - 4mv &= 139.9489 \times 10^4 - 1.71 = 139.487 \times 10^4 (\text{kg} \cdot \text{s/mm})^2 \end{aligned}$$

Calculating the expression $v > 0$, $\lambda^2 - 4mv > 0$, the root characteristic equation of the transfer function is a negative root. Therefore the engine control system is stable.

2. Analysis of the Transision Period of the Engine System

Because the mass of the engine injector needle valve is very small, $m \ll B = A_H^2 / K_{PH}$, we can omit the quadratic sum. The pressure variations of the combustion chamber that the temperature testing instrument measures monotonically rise and fall according to the exponential curve. Because of this, the engine control system can be simplified, and the transfer function formula changes to:

$$\phi(s) = \frac{K_0 K_1 A_H / K_{pH} \cdot \gamma}{(\lambda/\gamma)S + 1} = \frac{\xi}{TS + 1}$$

$\xi = K_0 K_1 A_H / K_{pH} \cdot \gamma$ is the amplitude coefficient

$T = \lambda/\gamma$ is the duration constant

According to the analysis of a link, when the combustion chamber pressure p_c arrives at the 95% of specified value, its transition period $t_p = 3T$. Therefore,

$$t_p = \frac{3(B + A_H / K_{pH})}{K - K_0 A_0 + K_0 K_1 A_H / K_{pH}} \quad (40)$$

Because the variable scope of one parameter in itself is not large, from the calculations of numeric value of the front side we see that:

$$B \ll A_H / K_{pH}, \quad |K - K_0 A_0| \ll K_0 K_1 A_H / K_{pH}$$

The interrelated expression of the transition period t_p can be simplified as:

$$t_p = \frac{3A_H}{K_0 K_1} \quad (41)$$

By equation (41) we can see that the transitional period is primarily dependent on the injector needle valve hydraulic pressure operation area A_H and the solenoid valve flow rate gain K_0 . In order to reduce the transitional period t_p , the injector needle valve hydraulic pressure operation area A_H must fully decrease. The properly enlarged solenoid valve circulation cross section A , increases the pulsewidth or raises the pulse operational frequency. Both are effective methods for reducing the transition period.

3. Analysis of the Engine System Steady State Error

By Fig. 9, the diagram of the engine control system, we can arrive at the formula for the deviation signal $E(t)$:

$$E(s) = \frac{1}{1+W(s)K_f} V_e(s)$$

where

$$W(s) = \frac{K_e K_f A_M / K_{PN}}{ms^2 + (B + A_M / K_{PN})s + K - K_e A_e}$$

In the engine control system that this text explains, control voltage $V_e(t)$ intakes by the form of rising function. Therefore, here we will only discuss the seat deviation of the rising intake signal. We will not grant discussion to the velocity error and acceleration error.

$$V_e(s) = \frac{K_f}{s}$$

where K_f is control voltage amplitude coefficient.

Using the alternate whole value theorem we can arrive at the common expression for steady-state error:

$$i(t) = \lim_{s \rightarrow 0} sE(s) = \frac{K_f}{1+W(0)K_f}$$

Substituting $W(0)$ we can arrive at the expression for the engine control system steady-state error:

$$i(t) = \frac{K - K_e A_e}{K - K_e A_e + K_e K_f K_f A_M / K_{PN}}$$

In the same way, $|K - K_e A_e| < K_e K_f K_f A_M / K_{PN}$

The steady-state error expression can be simplified to the following form:

$$i(t) = \frac{K - K_e A_e}{K_e K_f K_f A_M / K_{PN}} K_f$$

From equations (9), (10), (11), and (12) we obtain:

$$\frac{K_e}{K_{PH}} = \frac{2}{E_i} (P_o - P_{Ht})$$

Thus the expression for steady-state error is:

$$l(t) = \frac{(K - K_e A_e) E_i}{2 K_e K_{PH} (P_o - P_{Ht})} K_v \quad (42)$$

Increase the spring rigidity K , and reduce the injector needle valve hydraulic pressure operation area, and both can cause the steady-state error $l(t)$ to increase.

The thrust regulation weight is great, the deviation signal E_t is large, therefore steady-state error is great. There is more steady-state error when there is high thrust (P_{Ht} is more) regulation than when there is low thrust (P_{Ht} is less) regulation.

The preceding discussion is aimed at the condition of thrust rise. As to the condition of thrust decline, solenoid valve flow rate gain K_e and solenoid valve pressure coefficient K_{PH} use related equations (15), (16), (17) and (18). If we use the parameters of the exhaust solenoid valve, other parameters do not change, and we can obtain useful analytical results.

We still must point out, regarding the analysis for regulation performance of an engine system, we have not considered the steady-state error of the control system element in itself due to variations of structure and parameters influencing the rising of its degree of sensitivity. For instance, the solenoid valve needle valve movement intervals increase, the magnetic block increases, the forward edge of the needle valve opening enlarges, and causes steady-state error to increase. In the same way, the solenoid valve intake pressure P_o rises, the starting force increases, and can also cause the starting forward edge of the solenoid valve to enlarge, influencing the performance of the dynamic state and the steady-state. In addition, the non-linearity of the feedback pressure capsule can also influence

the regulation performance of the engine control system. Similar factors have not been included in the above analysis.

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