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MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

ADAPTIVE CONTROL OF LONGITUDINAL FLIGHT OF AIRCRAFT SYSTEM

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ABSTRACT

This paper present two proposals for adaptive control of supersonic aircraft. Inthe first proposal, the aircraft complete transfer function is controlled to behave according to a second order chosen model, while in the second proposal the inner loop of the aircraft transfer function is controlled to behave according to a first order model.

A modified gradient technique for a model reference adaptive control system with less order model is employed in the two proposals. Analog computer simulation resuits are presented and discussed .

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1. INTRODUCTION

In the historical development of aircraft systems, controllers were introduced to automatize straight and level flight, to enable flying by instrument without ground visibility and to simply augment the stability properties, and thus improve the handling qualities of the aircraft .

Part of the historical evolution in flight systems is that the region in which the aircraft can operate has been increased significantly, e.g. to high altititudes, high mach numbers, and even to major changes in the geometry of the aircraft, These signuficant changes in the aircraft dynamics had at least partially to be overcome by means of the control system and, in particular, the controller had to operate satisfactorily for a drastically changing aircraft. Extensive theoretical and experimental studies have been devoted to obtain a fairly accurate model of the dynamic behaviour of the aircraft for all possible flight conditions [1] , [2] . Using this knowledge of the possible parameters variations a control system should be designed in a way suitably adopted to the flight conditioin . Recent progress in the theory of adaptive control makes it applicable and well suited to solve flight control problems in an efficient way.

The available adaptive techniques are of the following type: local parametric optimization theory [3] , Lyapunov functions technique [4], and hyperstability and positive concepts [5]. Most of these techniques avoids the identification problem, but stresses that the order of the reference model must be the same as that of the nonadaptive system.

In an attempt to give a perspective for the possible application of adaptive control to aircraft systems, this paper presents, two proposals of adaptive control of a supersonic aircraft. The motivation of this work is based on one of the author earlier studies [6] in the solution of parameter tracking problems. In [6]. A modified gradient method was proposed to solve the problem of adaptive model reference control system when the model reference is less order than the adjustable system. In this paper the method was used to control the longitudinal motion of a supersonic aircraft when the reference model was chosen less order than the aircraft system equation. The organization of the rest of the paper is as follows: in section 2 a modified gradient method for the model reference adaptive control is presented. The system equations for the longitudinal motion of a hypothetical supersonic aircraft is given in section 3. The first proposal where the aircraft complete transfer function is controlled to behave according to a second order chosen reference model is given in section 4. In section 5, the second proposal, where the inner loop of the transfer function of the same aircraft is controlled to behave according to a first order reference model and conclusion appear in section 6.

2. PROPOSED ADAPTATION TECHNIQUE

Consider the following single input/single output model reference adaptive system shown in figure (1) and represented by:

a) The adjustable system

$$\sum_{i=0}^{n} \alpha_i \frac{d^i}{dt^i} C(t) = \sum_{i=0}^{\nu} B_i \frac{d^i}{dt^i} r(t) \quad ; n \geqslant \nu \tag{1}$$

$$\alpha_i = g_i + h_i \quad ; \quad i = 0, 1, \ldots, n \tag{2}$$

Where r(t) is the input, c(t) is the output, α_i and B_i are functions of the changing coefficients within the operation environments of the system, g_i are the variable parameters, and h_i are the controllable parameters.

b) The reference model

$$\sum_{i=0}^{m} a_i \frac{d^i}{dt^i} y(t) = \sum_{i=0}^{\mu} b_i \frac{d^i}{dt^i} r(t) \qquad m \geqslant \mu \tag{3}$$

Where y(t) is the output of the reference model, a_i and b_i are constant parameters of the system, and (m+1) equal to the number of controllable parameters of the adjustable system.

c) The generalized output error

$$e(t) = c(t) - y(t) \tag{4}$$

The parameters g_i are assumed to vary over extreme ranges within the operating environment of the nonadaptive system. Assuming that there exists a values of h_i for which the system will behave like the chosen reference model. The objective of the adaptation mechanism is to provide these values. Its input information is the generalized error e(t) and its output will be the instantaneous values of h_i. The problem can be formulated as: find the adaptive mechanism equations which, if no limitations are placed on the values of h_i, then regardless of what values g take, the outputs of both systems will be approximately identical whenever a quadratic function of the generalized error will be minimized. Considering the following error function:

$$f(e) = \sum_{i=0}^{m} \frac{1}{2} \left[q_i \frac{d^i}{dt^i} e(t) \right]^2 \tag{5}$$

where q_i are constant factors, Equation (5) assumed the availability of the derivatives of the error signal and it depends indirectly on the differences between the parameters of the adjusting system and the reference model which can be defined as:

$$\delta_i = \alpha_i - a_i \qquad (6)$$

If the parameters g_i vary slowly as compared to the basic time constants of the adjustable system and the reference model and the adaptation mechanism is designed to adjust the parameters h_i at a rate which is much greater than the rate of variation of g_i, the gradient optimization technique can be used and leads to the basic adaptation rule:

$$\frac{d}{dt}\alpha_i = -K_i \frac{\partial}{\partial \alpha_i} f(e) \qquad (7)$$

where K_i are arbitrary positive constants to be chosen by the designer and depend on the particular system considered.

If the development were to be based upon equation (7), the resulting design would require explicit knowledge of α_i and consequently g_i. Now suppose that α_i are treated as constant, and a_i are to be adjusted so as to cause the differences δ_i to approach the same values then the variations in a_i becomes

$$\frac{d}{dt} a_i = -K_i \frac{\partial}{\partial a_i} f(e) \qquad (8)$$

The objective is not to change a_i, however, to change α_i. Since from equation (6) the same changes in δ_i can be obtained by substracting Δa_i from α_i, rather than adding them to a_i. The resulting instantaneous rates of adjusting α_i can be written as:

$$\frac{d}{dt}\alpha_i = K_{i\alpha} \frac{\partial}{\partial a_i} f(e) \qquad (9)$$

When equation (5) was substituted into equation (9), and the indicated partial derivative was carried out equation (9) becomes:

$$\frac{d}{dt}\alpha_i = -K_{i\alpha}\left[\sum_{J=0}^{m} q_j \frac{d^j e}{dt^j}\right]\left[\sum_{J=0}^{m} q_j \frac{\partial}{\partial a_i} \frac{d^j}{dt^j} y(t)\right] \qquad (10)$$

Introducing the notation:

$$u_{i\alpha} = \frac{\partial y}{\partial a_i} \quad ; \quad i = 0, 1, \cdots m \qquad (11)$$

Again, assuming that the parameters δ_i are changing with slow rates, the order of differentiation in the right-hand side of equation (10) can be interchanged, yielding to

$$\frac{d}{dt}\alpha_i = -K_{i\alpha}\left[\sum_{j=0}^{m} q_j \frac{d^j e}{dt^j}\right]\left[\sum_{j=0}^{m} q_j \frac{d^j}{dt^j} u_{j\alpha}\right] \qquad (12)$$

Since it is assumed that the adaptation mechanism will be designed so as to adjust the controllable parameters h_i in a rate greater than the changes in g_i. The rates of g_i can be neglected and from equation (12) the rates of h_i can be written as:

$$\frac{dh_i}{dt} \simeq \frac{d\alpha_i}{dt} = K_{i\alpha}\left[\sum_{j=0}^{m} q_j \frac{d^j e}{dt^j}\right]\left[\sum_{j=0}^{m} q_j \frac{d^j}{dt^j} u_{i\alpha}\right] \qquad (13)$$

The only unknown quantities in equations (13) are $u_{i\alpha}$. Considering the differential equation of the reference model (3), and taken the partial derivative of both sides with respect to the parameters a_i, treating the derivatives of y with respect to time as trivial partial derivative, and interchanging the order of differentiation and employing the notation introduced in equation (11), the following set of equations for $u_{i\alpha}$ can be written as:

$$\sum_{i=0}^{m} a_i \frac{d^i u_{j\alpha}}{dt^i} = -\frac{d^j y}{dt^j} \quad , \quad j=0,\dots,m \qquad (14)$$

Equation (14) represent a set of differential equations with available forcing functions and their solutions provides the values of u for equations (13).
Similarly for the case of the parameters B_i, the following adaptive mechanism equations are required.

$$\frac{dB_i}{dt} = -K_{iB}\left[\sum_{j=0}^{m} q_j \frac{d^j e}{dt^j}\right]\left[\sum_{j=0}^{m} q_j \frac{d^j}{dt^j} u_{iB}\right] \qquad i=0,\dots,\nu \qquad (15)$$

$$\sum_{i=0}^{m} a_i \frac{d^i u_{iB}}{dt^i} = \frac{d^j}{dt^j} r(t) \quad ; \; j=0,1,\dots,\nu \qquad (16)$$

$$\text{Where} \quad U_{iB} = \frac{\partial y}{\partial b_i} \quad i=0,1,\dots,\nu \qquad (17)$$

The four sets of equations (13), (14), (15), and (16) represent the adaptive mechanism algorithm required for adaptation of the adjusting system to follow the reference model. The complete set of differential equations which describes the adaptive system operation can be written as:

$$\sum_{i=0}^{n} \alpha_i \frac{d^i c(t)}{dt^i} = \sum_{i=0}^{\nu} B_i \frac{d^i}{dt^i} r(t)$$

$$\sum_{i=0}^{m} a_i \frac{d^i}{dt^i} y(t) = \sum_{i=0}^{\mu} b_i \frac{d^i}{dt^i} r(t)$$

$$\sum_{i=0}^{m} a_i \frac{d^i}{dt^i} u_{j\alpha} = -\frac{d^j}{dt^j} y(t) \quad ; \quad j=0,\dots,m$$

$$\sum_{i=0}^{m} a_i \frac{d^i}{dt^i} u_{jB} = \frac{d^j}{dt^j} r(t); \quad j = 0, 1, \ldots, \nu$$

$$\frac{dh_i}{dt} = -K_{i\alpha} \left[\sum_{j=0}^{m} q_j \frac{d^j e(t)}{dt^j} \right] \left[\sum_{j=0}^{m} q_j \frac{d^j}{dt^j} U_{i\alpha} \right]; \quad i = 0, \ldots, m$$

$$\frac{d\beta_i}{dt} = -K_{iB} \left[\sum_{j=0}^{m} q_j \frac{d^j e(t)}{dt^j} \right] \left[\sum_{j=0}^{m} q_j \frac{d^j}{dt^j} U_{iB} \right]; \quad i = 0, \ldots, \nu \qquad (18)$$

2 - MATHEMATICAL MODEL OF AIRCRAFT SYSTEM

It is well know that the short period mode can be used to represent the longitudinal dynamics of supersonic aircraft with sufficient accuracy due to its simplicity 1 . The fundamental transfer functions that describe the dynamical motions of an aircraft in the longitudinal-vertical plane of motion are given by:

$$\frac{\alpha}{\delta_e} = \frac{n_{35}}{p^2 + 2d\omega_o p + \omega_o^2} \qquad (19)$$

$$\frac{\theta}{\delta_e} = \frac{n_{35}(p + n_{22})}{p(p^2 + 2d\omega_o p + \omega_o^2)} \qquad (20)$$

$$\omega_o = \sqrt{n_{22} n_{23} + n_{32}} \quad \& \quad d = \frac{n_{22} + 33 + n_{30}}{2\omega_o} \qquad (21)$$

Where:

- α is the change in angle of attack
- θ is the change in pitch angle
- δ_e is the change in elevator deflection
- n_{ij} are the coefficients for the short period mode

For the purpose of illustration, consider a hypothetical aircraft with the following basic parameters:

Mass of aircraft	m = 8100 kg
Wing area	s = 32.4 m
Wing span	ℓ = 9.52 m
length of mean aerodynamic chord	b = 3.4 m

For such aircraft, the numerical values of the coefficients for the short period mode n_{ij} were calculated for initial horizontal flight also the damping factor d and the natural frequency ω_o , the calculations were performed for different altitudes and given in table (1). For the supersonic aircraft described above a typical classical autopilot can be represented by the following equation [7];[8]:

$$\delta e = \frac{K_1}{p(Tp+1)} \left[K_2 (\theta - \theta_r) + (\varepsilon + \eta p) p \theta\right] \tag{22}$$

Where:

θ_r the input reference signal

η the accelerometer gain

ε the rate gyro gain

T time constant of servomechanism

K_1 the amplifier gain

K_2 the vertical gyro gain.

The block diagram of the complete aircraft system is given in figure (2). From which the transfer function representing the total behaviour of the system can be written as:

$$\frac{\theta(p)}{\theta_r(p)} = \frac{-n_{35} K_1 K_2 (p + n_{22})}{a_0 p^5 + a_1 p^4 + a_2 p^3 + a_3 p^2 + a_4 p + a_5} \tag{23}$$

Where $a_0 = T$

$$a_1 = 1 + T(n_{22} + n_{33} + n_{30})$$

$$a_2 = n_{22} + n_{33} + n_{30} - n_{35} K_1 \eta + T(n_{32} + n_{22} n_{33})$$

$$a_3 = n_{22} n_{33} + n_{32} - n_{22} n_{35} K_1 \eta - n_{35} K_1 \varepsilon$$

$$a_4 = -n_{22} n_{35} K_1 \varepsilon - n_{35} K_1 K_2$$

$$a_5 = -n_{35} n_{22} K_1 K_2$$

It is clear that the behaviour of the aircraft system will vary according to the flight altitude because of the variation of the coefficients n_{ij}. For this reason the need for adaptive

control for such aircraft is required. Sensitivity analysis and analog computer simulation for the above aircraft shows that the aircraft system parameters which have the main effect on the transient response are the accelerometer gain η and the rate gyro gain ε. In the following sections two proposals for the adaptation of the aircraft are given.

4- FIRST ADAPTIVE PROPOSAL FOR THE AIRCRAFT SYSTEM:

The first proposal for the adaptation of the aircraft system consist of controlling the feedback parameters η and ε by the adaptive mechanism so that the aircraft system response behave according to a second order reference model. The block diagram of the proposed adaptation scheme is given in Figure (3).

According to the proposed principle of adaptation given in section 2 let the reference model and the error function equations be:

$$\alpha_0 \frac{d^2}{dt^2} y(t) + \alpha_1 \frac{d}{dt} y(t) + \alpha_2 y(t) = \theta_r(t) \tag{24}$$

$$f(e) = \tfrac{1}{2} \left[q_0 e(t) + q_1 \dot{e}(t) + q_2 \ddot{e}(t)\right]^2 \tag{25}$$

The equations representing the dynamics of the adaptation mechanism are:

$$\begin{aligned} \dot{a}_4 &= -c_1 [q_0 e + q_1 \dot{e} + q_2 \ddot{e}][q_0 u_1 + q_1 \dot{u}_1 + q_2 \ddot{u}_1] \\ \dot{a}_3 &= -c_2 [q_0 e + q_1 \dot{e} + q_2 \ddot{e}][q_0 u_2 + q_1 \dot{u}_2 + q_2 \ddot{u}_2] \end{aligned} \tag{26}$$

and

$$\begin{aligned} \alpha_0 \ddot{u}_1 + \alpha_1 \dot{u}_1 + \alpha_2 u_1 &= -\dot{y}(t) \\ \alpha_0 \ddot{u}_2 + \alpha_1 \dot{u}_2 + \alpha_2 u_2 &= -\ddot{y}(t) \end{aligned} \tag{27}$$

From Equations (23), differentiating a_4 and a_3 with respect to time, and considering that the time derivatives of the aircraft parameters n_{ij} are neglected, the time rates at which the accelerometer gain η and the rate gyro gain ε will be

$$\dot{\varepsilon} = -\frac{\dot{a}_4}{n_{22} n_{35} K_1} \tag{28}$$

$$\dot{\eta} = -\frac{\dot{a}_3}{n_{22} n_{35} K_1} + \frac{\dot{a}_4}{n_{22}^2 n_{35} K_1} \tag{29}$$

The rate of changing the accelerometer η in equation (28) depends on both $\dot{a}_4$ and $\dot{a}_3$, but to secure the stability of the adaptive process, it will be considered that $\dot{\eta}$ will be controlled only by the changes in $\dot{a}_3$, also the coefficient $\left[-\frac{1}{n_{22} n_{35} K_1}\right]$ will be absorbed into the coefficients c_1 and c_2.

The complete adaptive system were simulated on analog computer with the reference model equation as:

$$0.0625\, \ddot{y} + 0.35\, \dot{y} + y = \theta r \tag{30}$$

The numerical values of the autopilot's coefficients K_1 and K_2

and the time constant of the servosystem were chosen, as to get the best transient response, to be:

$$K_1 = 20 \quad \text{and} \quad K_2 = 16 \quad \text{and} \quad T = 0.05 \text{ sec.} \tag{31}$$

The best function of the adaptive mechanism, where obtained for the following values of the proportionality factors:

$$q_o = q_1 = q_2 = 1$$

$$c_1 = 19.81 \qquad c_2 = 0.589 \tag{32}$$

The aircraft autopilot system was excited by input pulses of

amplitude 0.09° and with 5 seconds duration in one polarity, then the convergence of autopilot's coefficients η and ε to an optimum value, from extreme initial values, was checked, In Figure (4), the aircraft was set to the parameters of altitude 5 km. It was found that the parameters η and ε converged nearly to the same optimum value after 5 changes of the input level, from extremely large initial values. Figure (5) represents the same trajectories of η and ε when the aircraft parameters set to the values of altitude 25 km. The system was simulated for a step input, for altitudes (5, 10, 15, 20, and 25 km), with the adaptive autopilot parameters initially are $\eta_o = 1.12$ and $\varepsilon_o = 5.7$.

Figure (6) represent the responses of the aircraft system θ; rate of pitch $\dot{\theta}$, the changes in the angle of attack α, and the generalized error e.

5. SECOND ADAPTIVE PROPOSAL.

In this proposal the same aircraft controlled with the same autopilot is considered. The difference is that the adaptive mechanism will be designed to control the two parameters and as for the inner loop, to behave according to a first order reference model. The block diagram of the adaptation scheme is shown in figure (7).
The transfer function of the inner loop was derived to be:

$$\frac{\dot{\theta}(p)}{\mu(p)} = \frac{-n_{35}K_1(p+n_{22})}{b_o p^4 + b_1 p^3 + b_2 p^2 + b_3 p + b_4} \tag{33}$$

Where

$$b_o = T$$

$$b_1 = 1 + T(n_{22} + n_{33} + n_{30})$$

$$b_2 = n_{22} + n_{33} + n_{30} - n_{35}K_1\eta + T(n_{32} + n_{22}n_{33})$$

$$b_3 = n_{22}n_{33} + n_{32} - n_{22}n_{35}K_1\eta - n_{35}K_1\varepsilon$$

$$b_4 = -n_{22}n_{35}K_1\varepsilon$$

The reference model and the error function was chosen to be:

$$a_1 \dot{z} + a_0 z = \mu \tag{34}$$

$$f(e) = \frac{1}{2}[q_0 e + q_1 \dot{e}]^2 \tag{35}$$

The equations representing the dynamics of the adaptive mechanism in this case are:

$$\begin{aligned} \dot{b}_4 &= -c_0 (q_0 e + q_1 \dot{e})(q_0 u_0 + q_1 \dot{u}_0) \\ \dot{b}_3 &= -c_1 (q_0 e + q_1 \dot{e})(q_0 u_1 + q_0 \dot{u}_1) \end{aligned} \tag{36}$$

and

$$\begin{aligned} a_1 \dot{u}_0 + a_0 u_0 &= -z \\ a_1 \dot{u}_1 + a_0 u_1 &= -\dot{z} \end{aligned} \tag{37}$$

From equations (33), differentiating b_4 and b_3 with respect to time, considering the same assumptions stated before, the time rates at which the accelerometer gain η and the rate gyro gain ε will be:

$$\dot{\varepsilon} = -\dot{b}_4 / n_{22} n_{35} K_1 \tag{38}$$

$$\dot{\eta} = -\dot{b}_3 / n_{22} n_{35} K_1 + \dot{b}_4 / n_{22}^2 n_{35} K_1 \tag{39}$$

Taking into account the same assumptions as in the first proposal the rate of change of the accelerometer gain η will depend only on $\dot{b}_3$.

The complete adaptive system was simulated on the analog computer with the reference model equation as:

$$0.5 z + z = \mu \tag{40}$$

The numerical values of the autopilot's coefficients K_1 and K_2 and the time constant of the servosystem were chosen to be:

$$K_1 = 20, \quad K_2 = 2.2 \text{ and } T = 0.05 \text{ sec.} \tag{41}$$

The adaptive mechanism parameters was taken as:

$$\begin{aligned} c_0 &= 31.25 \qquad\qquad c_1 = 3.9 \\ q_0 &= q_1 = 1 \end{aligned} \tag{42}$$

The aircraft autopilot system was excited by input pulses of amplitude 0.15° and 5 seconds duration in one polarity, then the covergence of the same parameters η and ε was checked. In figure (8), the aircraft parameters were set to the values of altitude 5 km, the parameters η and ε converged nearly to the optimum values after 5 changes of the input level from extremely large initial values. The system were simulated with aircraft parameters at altitude 25 km and the convergence result as shown in Figure (9). The system was simulated for a step input for altitudes 5, 10, 15, 20, 25 km, with the adaptive autopilot parameters initially are η_0 =0.51 and ε_0 =0.94. Figure (10) represents the responses of the aircraft system θ ,the rate of pitch $\dot{\vartheta}$, the changes in angle of attack α and the generalized error e.

6. CONCLUSION:

The concept of a proposed gradient method is used to seek out solution of the problem of adaptive control for aircraft system where the reference model used is less order than the aircraft system. Two proposals for adaptation of the longitudinal flight of aircraft system were presented. In both cases, the suggested technique proved to secure the needs of aircraft stability and control. The adaptive mechanism is quite reasonable from the stand point of actual physical hardware. In the second proposal the control of the inner loop of the aircraft system leads to a considerable simplification of the mechanization of the adaptive mechanism. Analog computer simulation for the two cases shows that the stability of the adaptive system depend on the choice of the adaptive mechanism parameters.

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FIGURE CAPTIONS

Figure (1) Proposed adaptation scheme

Figure (2) Block diagram of the aircraft autopilot system

Figure (3) First adaptive proposal scheme for the aircraft system

Figure (4) Convergence of the aircraft parameters at altitude of 5 Km

Figure (5) Convergence of the aircraft parameters at altitude of 25 Km

Figure (6) Rsponses of the aircraft adaptive system at different altitudes for the first adaptation proposal

Figure (7) Second adaptive proposal scheme for the aircraft system

Figure (8) Convergence of the aircraft parameters at altitude of 5 Km for the second proposal

Figure (9) Convergence of the aircraft paraemeters at altitude of 25 Km for the second proposal

Figure (10) Responses of the aircarft adaptive system at different altitudes for the second adaptation proposal

Table (1) The aircraft short period mode coefficients n_{ij} for different altitudes.

H(km)	5	10	15	20	25
n_{30}	0.68	0.507	0.28	0.1175	0.047
n_{22}	1.29	1.06	0.672	0.34	0.168
n_{32}	4.85	24.7	25.3	18.6	13.3
n_{33}	1.5	1.23	0.782	0.391	0.184
n_{35}	-15.9	-17.0	-13.15	-7.17	-4.67
d	0.665	0.274	0.169	0.098	0.0548
ω_o	2.61	5.1	5.08	4.32	3.642

Table (1)

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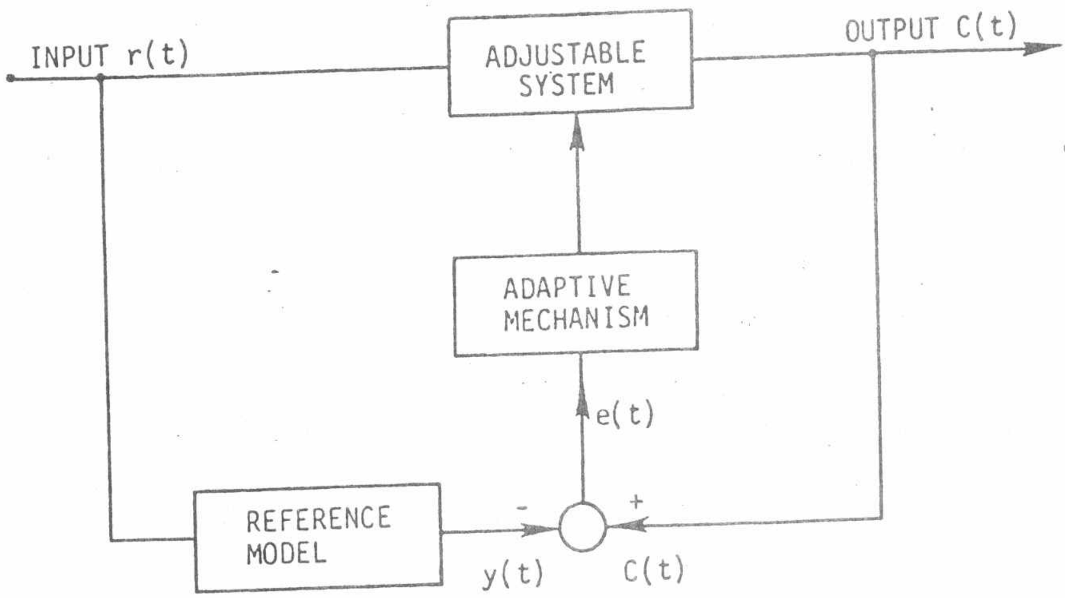

Figure 1.

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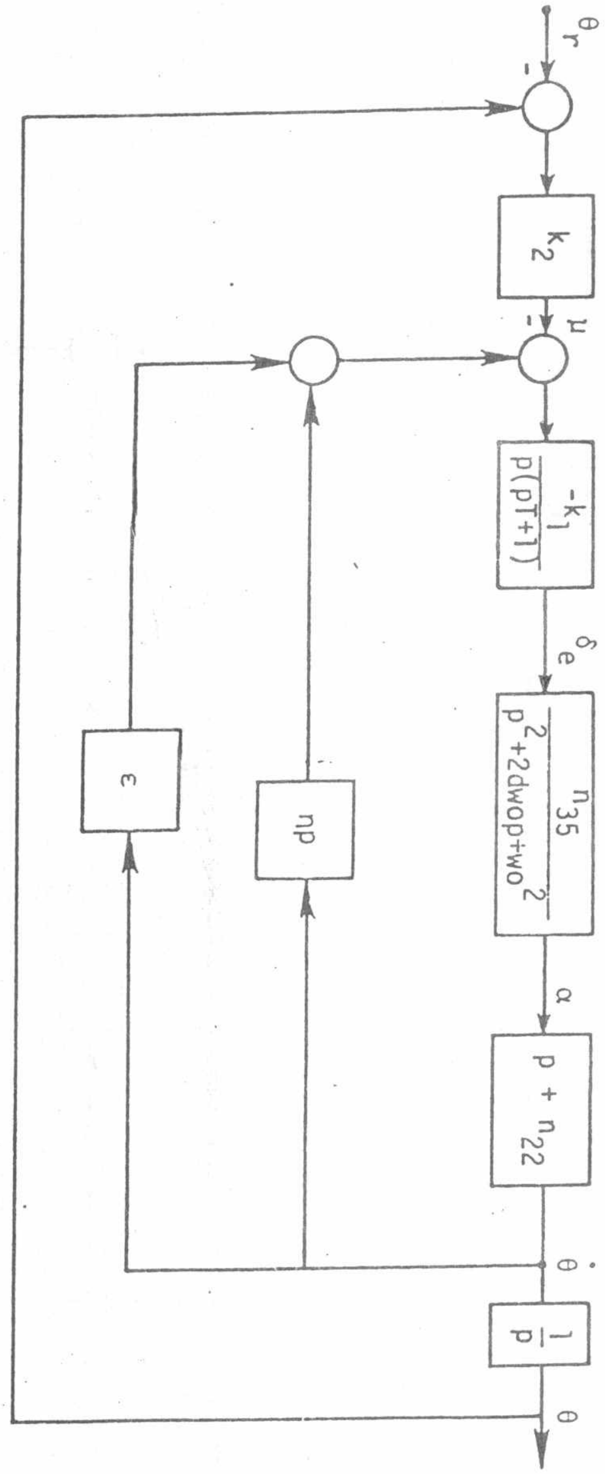

Figure 2.

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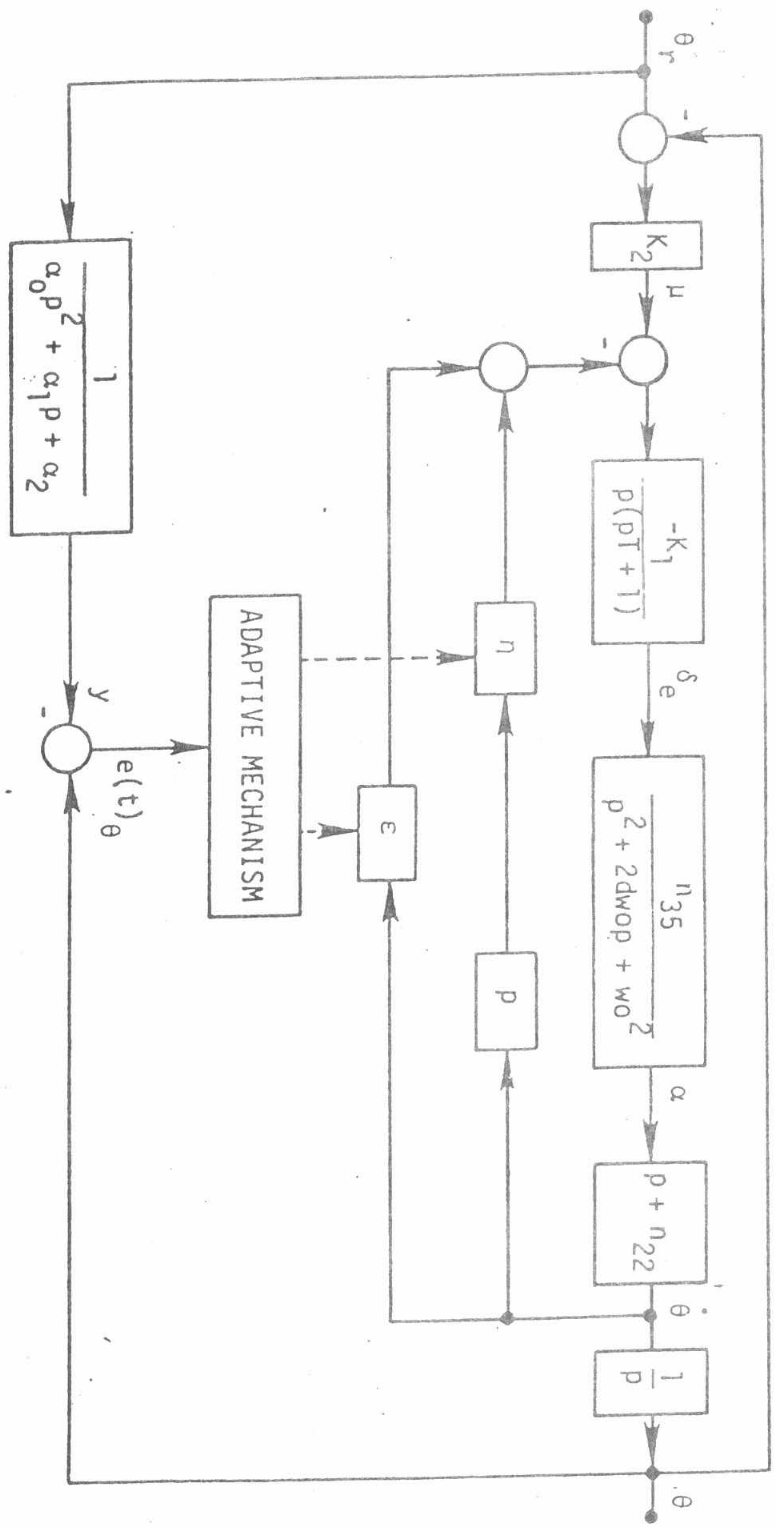
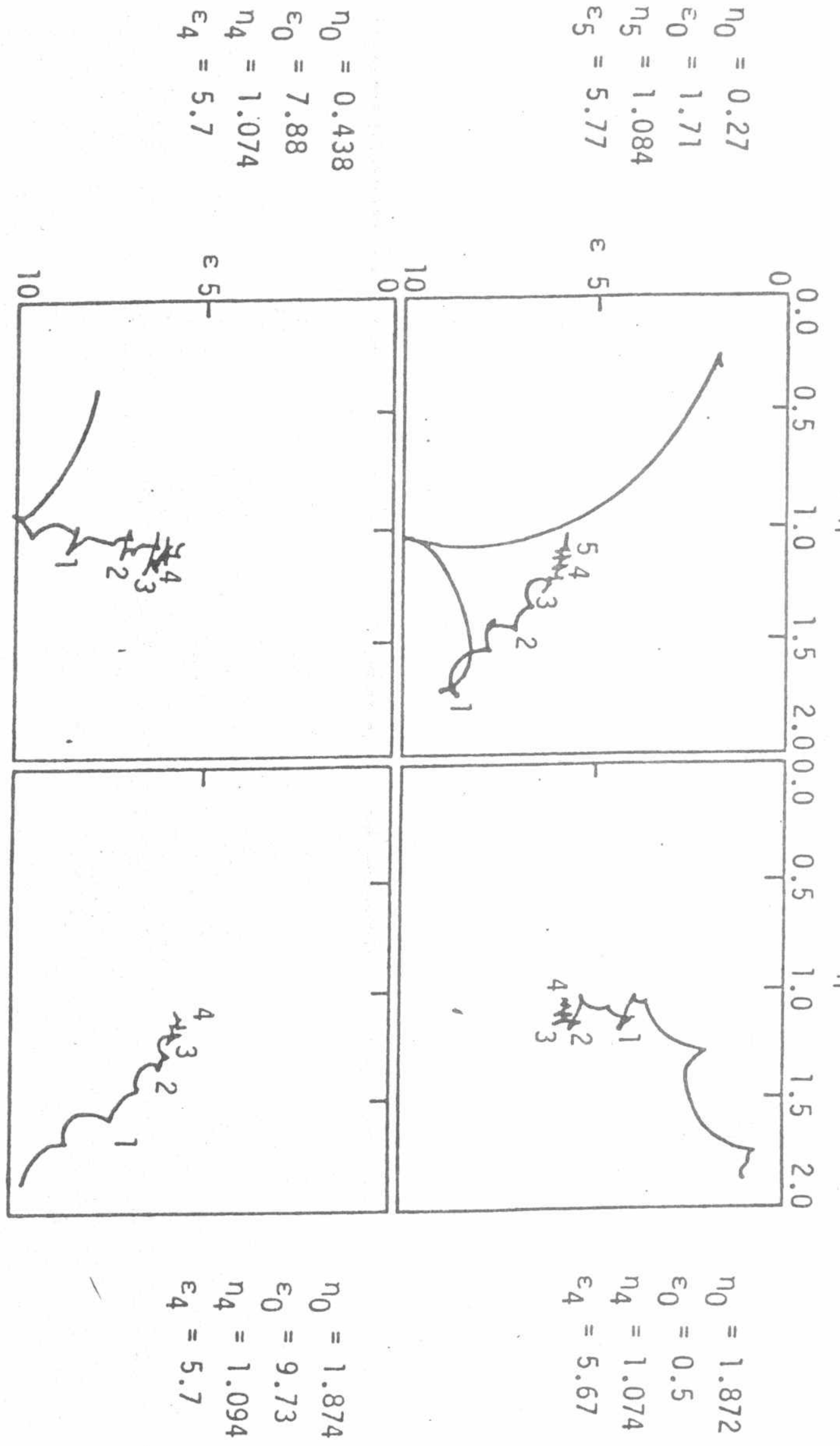


Figure 3.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ε0 = 1.71
n5 = 1.084
ε5 = 5.77
n0 = 0.438
ε0 = 7.88
n4 = 1.074
ε4 = 5.7
n0 = 1.872
ε0 = 0.5
n4 = 1.074
ε4 = 5.67
n0 = 1.874
ε0 = 9.73
n4 = 1.094
ε4 = 5.7
n
ε
0.0
0.5
1.0
1.5
2.0
0
5
10

Figure 4.

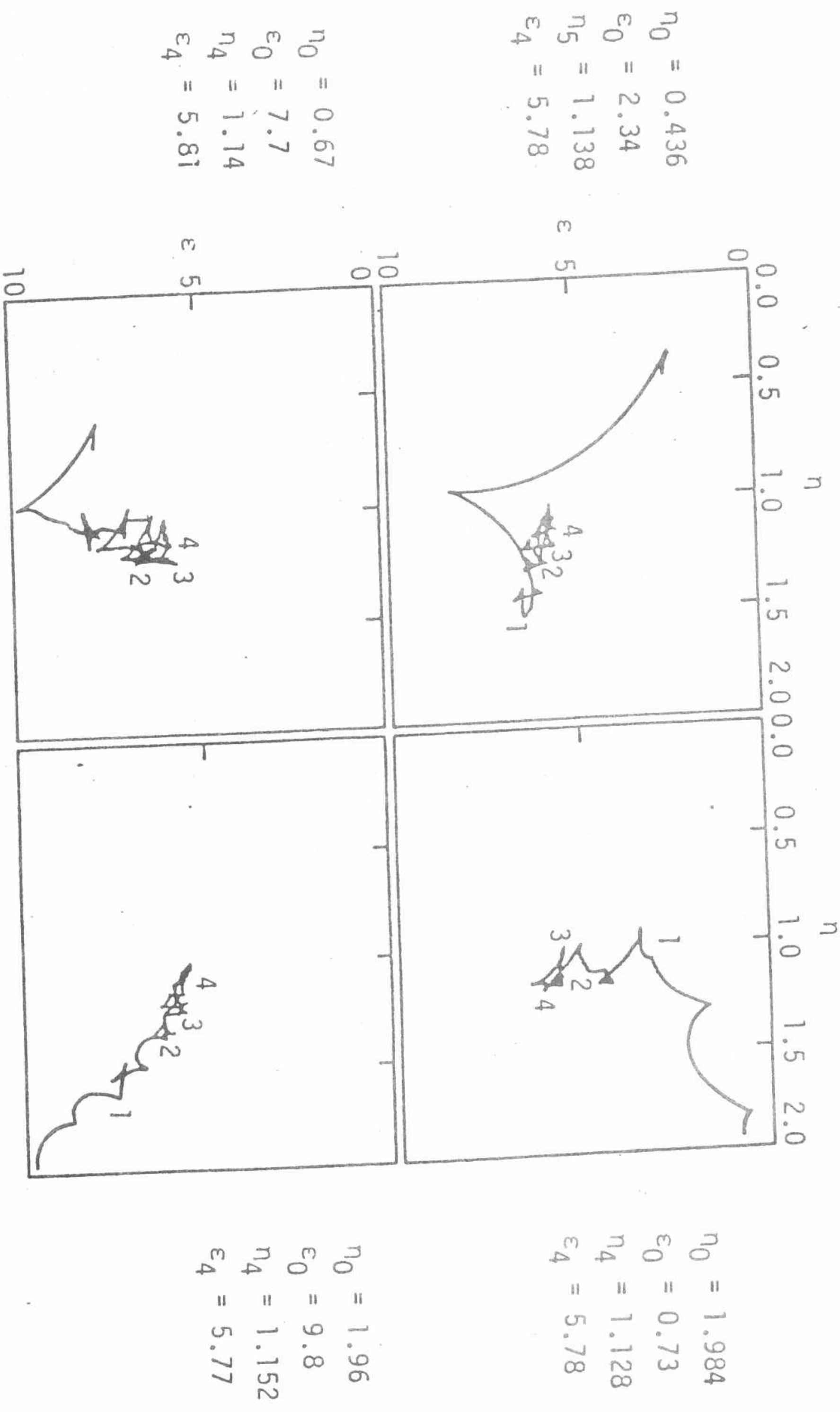
$\eta_0 = 0.436$
$\varepsilon_0 = 2.34$
$\eta_5 = 1.138$
$\varepsilon_4 = 5.78$
$\eta_0 = 1.984$
$\varepsilon_0 = 0.73$
$\eta_4 = 1.128$
$\varepsilon_4 = 5.78$
$\eta_0 = 0.67$
$\varepsilon_0 = 7.7$
$\eta_4 = 1.14$
$\varepsilon_4 = 5.81$
$\eta_0 = 1.96$
$\varepsilon_0 = 9.8$
$\eta_4 = 1.152$
$\varepsilon_4 = 5.77$
η
ε
0.0
0.5
1.0
1.5
2.0
0
5
10
1
2
3
4

Figure 5.

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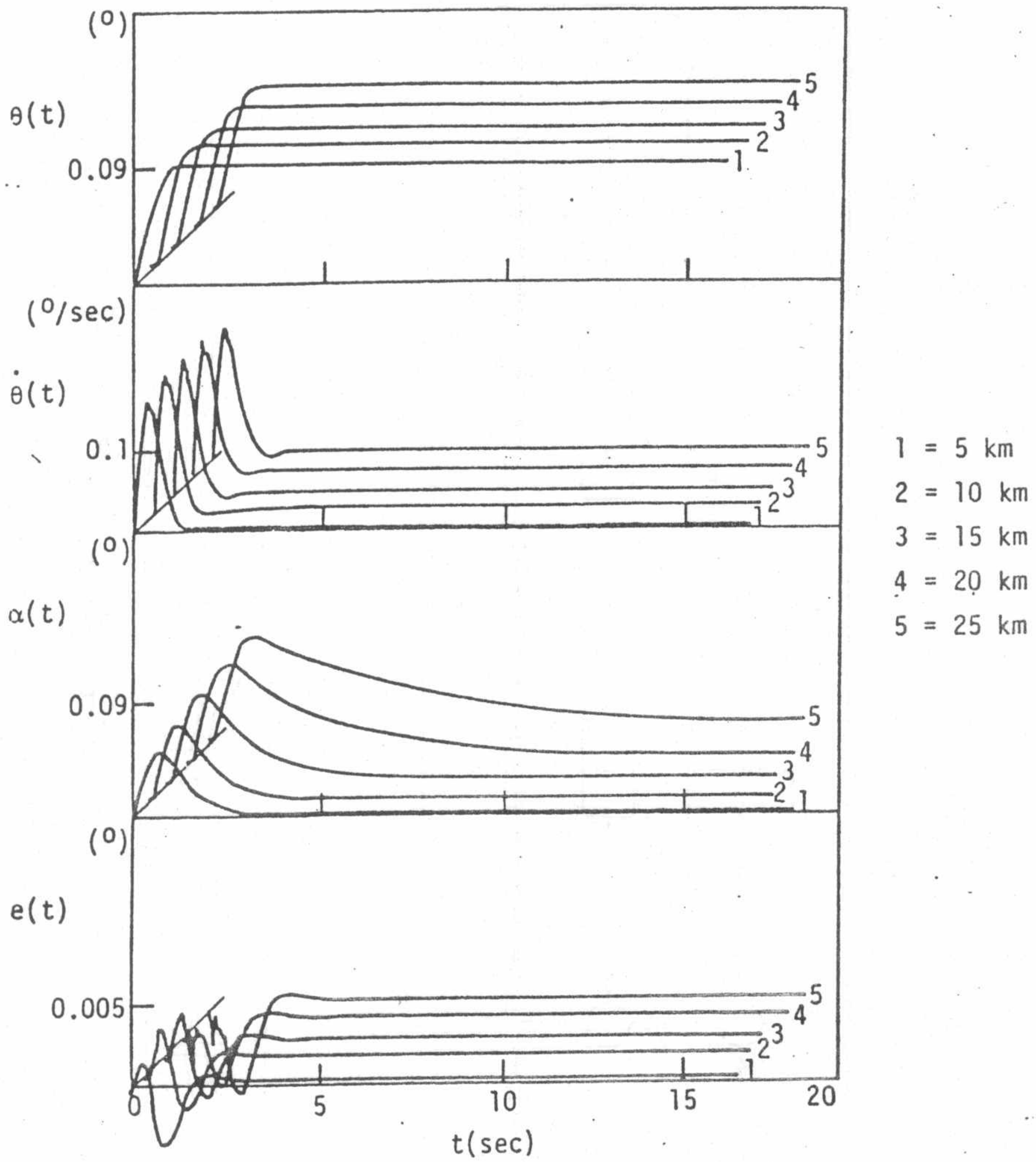

Figure 6.

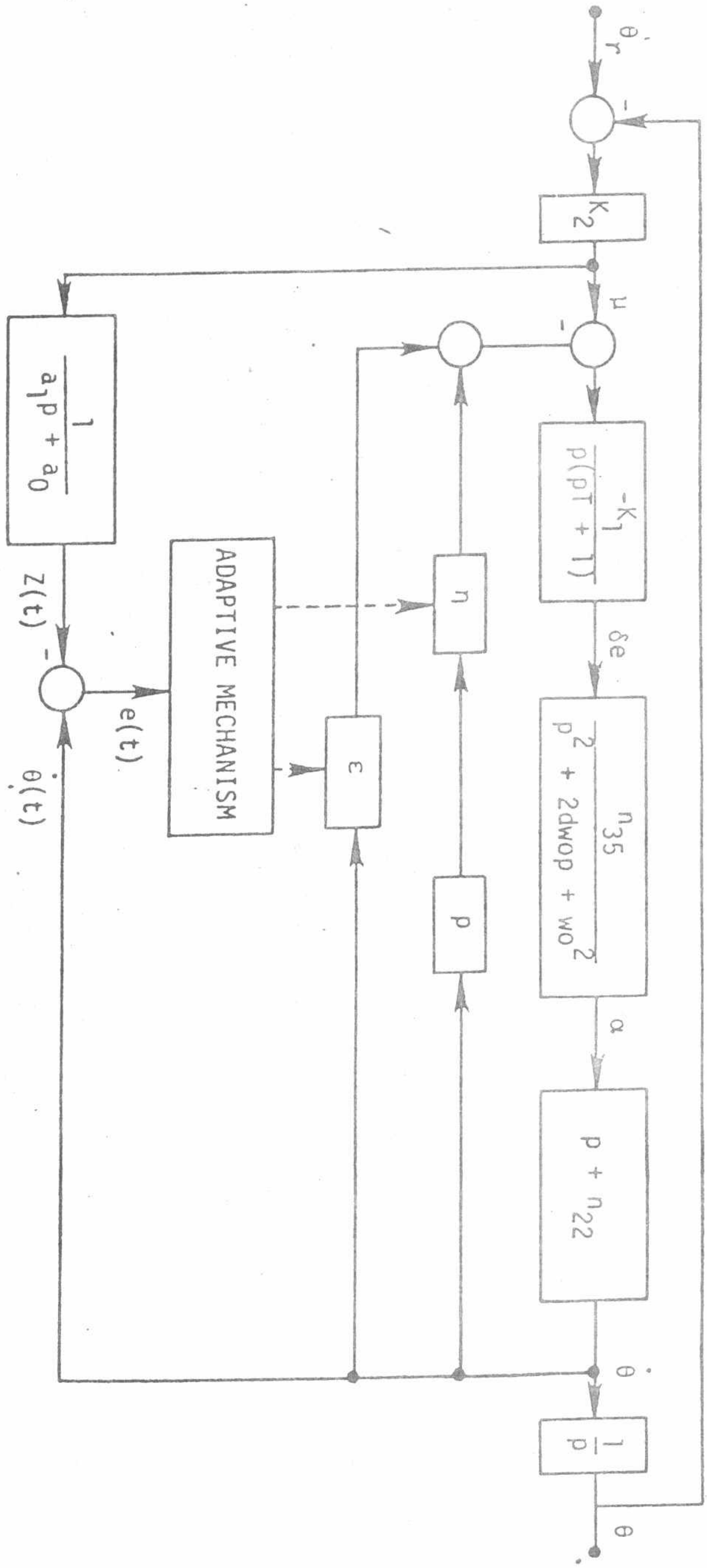
θ'r
K2
μ
-K1
p(pT + 1)
δe
n35
p2 + 2dwop + wo2
α
p + n22
θ̇
1
p
θ
1
a1p + a0
Z(t)
ADAPTIVE MECHANISM
e(t)
θ̇(t)
n
ε
p

Figure 7.

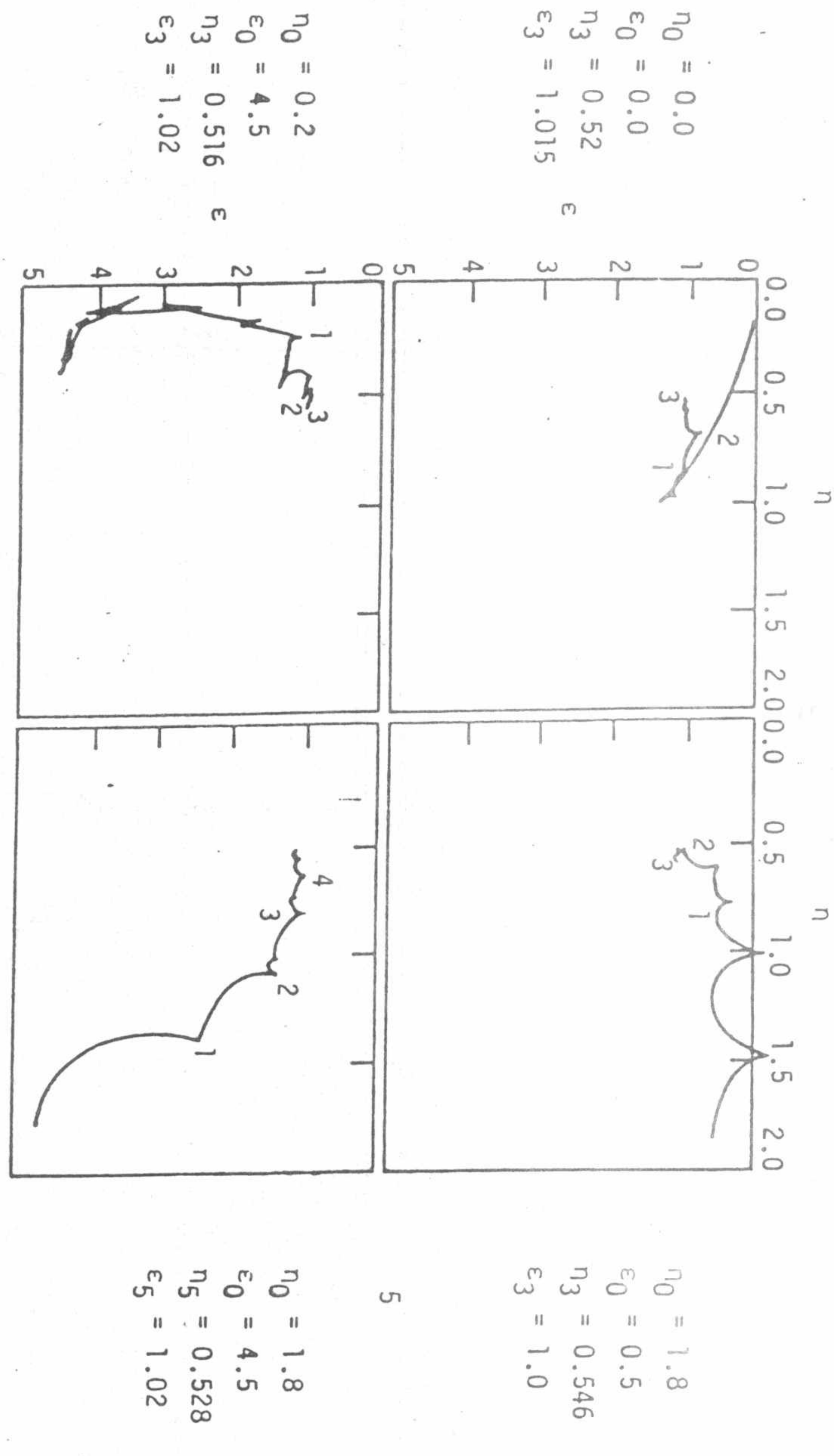
$n_0 = 0.0$
$\varepsilon_0 = 0.0$
$n_3 = 0.52$
$\varepsilon_3 = 1.015$
$n_0 = 1.8$
$\varepsilon_0 = 0.5$
$n_3 = 0.546$
$\varepsilon_3 = 1.0$
$n_0 = 0.2$
$\varepsilon_0 = 4.5$
$n_3 = 0.516$
$\varepsilon_3 = 1.02$
$n_0 = 1.8$
$\varepsilon_0 = 4.5$
$n_5 = 0.528$
$\varepsilon_5 = 1.02$
n
ε

Figure 8.

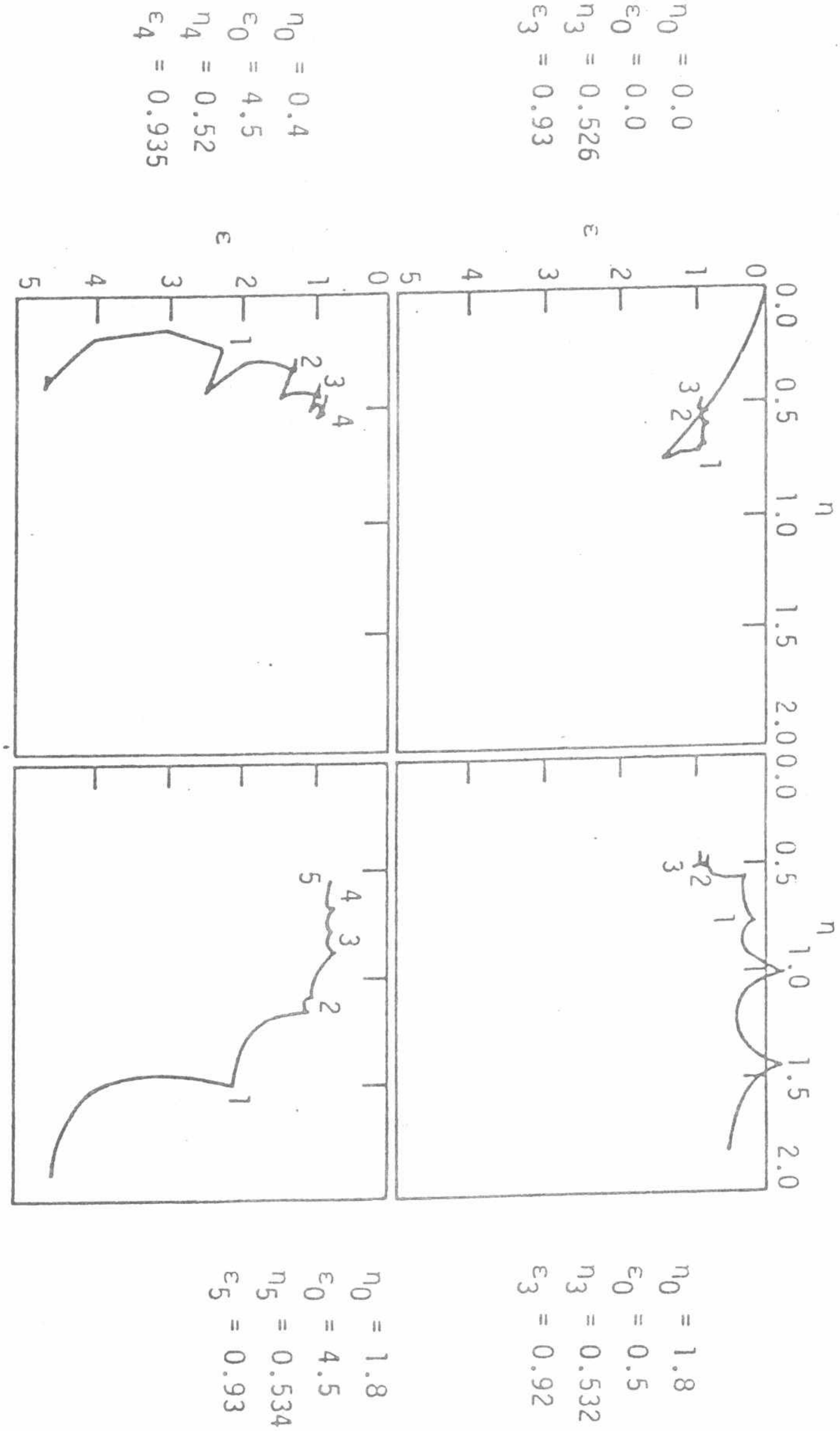
$n_0 = 0.0$
$\varepsilon_0 = 0.0$
$n_3 = 0.526$
$\varepsilon_3 = 0.93$
$n_0 = 0.4$
$\varepsilon_0 = 4.5$
$n_4 = 0.52$
$\varepsilon_4 = 0.935$
$n_0 = 1.8$
$\varepsilon_0 = 0.5$
$n_3 = 0.532$
$\varepsilon_3 = 0.92$
$n_0 = 1.8$
$\varepsilon_0 = 4.5$
$n_5 = 0.534$
$\varepsilon_5 = 0.93$
n
ε

Figure 9.

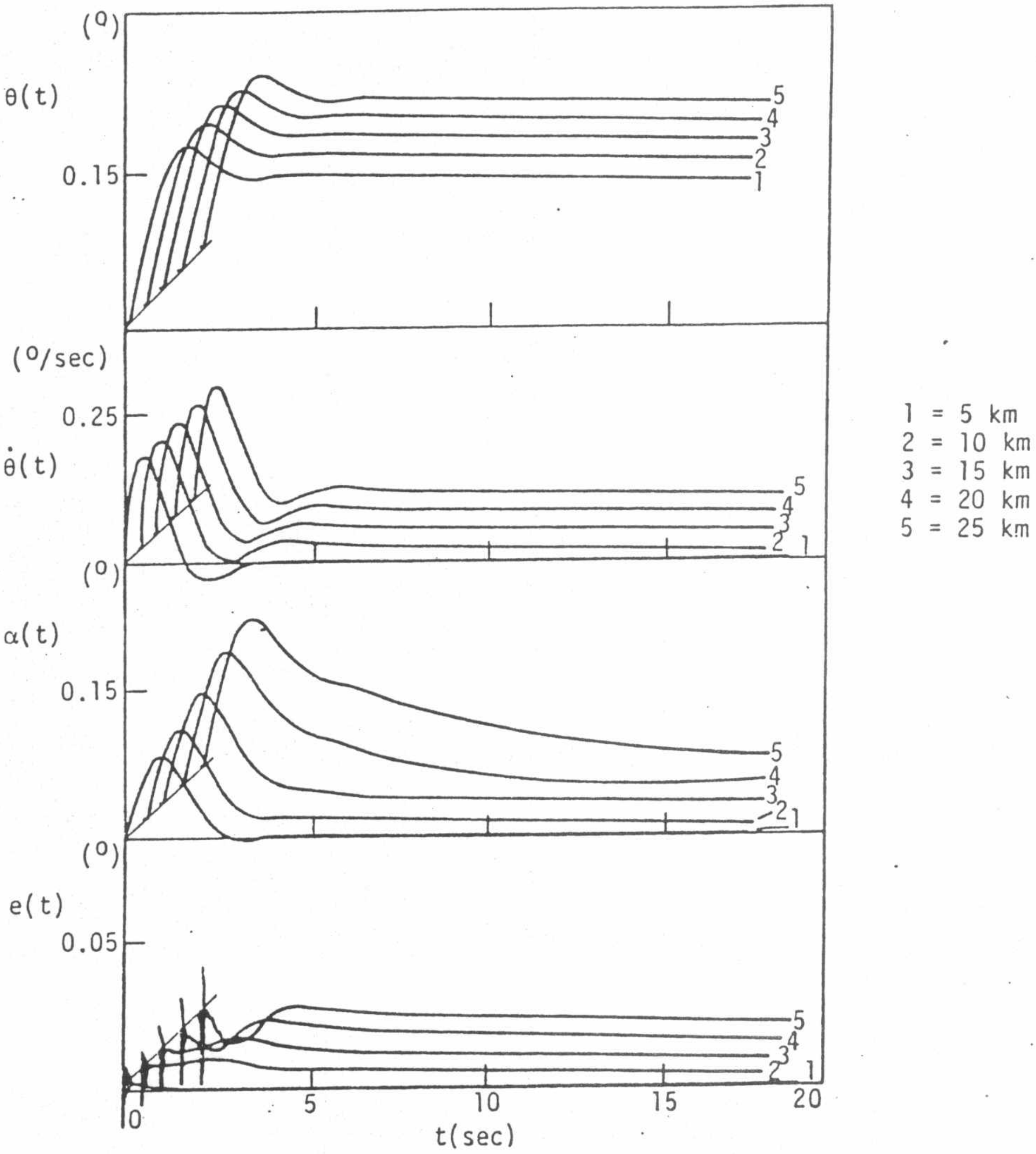
(°)
θ(t)
0.15
5
4
3
2
1
(°/sec)
0.25
θ̇(t)
(°)
α(t)
0.15
(°)
e(t)
0.05
0
5
10
15
20
t(sec)
1 = 5 km
2 = 10 km
3 = 15 km
4 = 20 km
5 = 25 km

Figure 10.