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REAL-TIME ANALYSIS OF MICROCOMPUTER-BASED ADAPTIVE FLIGHT CONTROL SYSTEMS *

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ABSTRACT

A new adaptive controller combined with a conventional controller applied to the missile control system has been developed [1] . This paper is the further study on the possibility for implementing a digital adaptive controller . A laboratory general-purpose , real-time simulation configuration and its software package , which is a versatile hardware and software combination were also developed . Some practical problems encountered in real-time control are discussed and results obtained from the digital-analog simulation are in good agreement with those of using the all digital simulation . Real-time hybrid simulation shows that the performance of the system using adaptive controller is superior to that without adaptive controller . The complete software package programmed in hybrid language is recommended .

I. INTRODUCTION

The digital autopilot technology has been developed significantly over the last ten years for tactical weapon applications [2] - [4] . A successful analog adaptive autopilot applied to the air-to-air missile was reported in 1977 [5] . They selected a simple method to implement the parameter identification of the missile body , so called external sinusoidal signal excitation method .The disadvantage is that the adaptive range is limited . Since then , many researchers have become to develop the digital adaptive control used in industry [6] due to miniaturization , availability , flexibility, and low cost of digital hardware . But to the author's knowledge , few papers have been reported in the open literature on the design of the digital adaptive autopilot used in the tactical weapons .

The parameters of midcourse air-to-air missile vary widely and significantly . Sometimes , the system is nonminimum-phase one . It is difficult to satisfy performance specifications for different altitude trajetories using a pure classical controller.However, to maintain good performance over a wide range of the altitudes and speeds of the missile , digital adaptive control methods may prove suitable . Among various adaptive methods , model reference adaptive control (MRAC) is most widely used in high-speed control systems and relatively easy to implement . But it is difficult to implement stable model following for such a high order missile dynamics using only adaptive controller . For these reasons , we have developed a new adaptive scheme based on the original,conventional autopilot without changing its configuration .

The paper is the extention of the reference [1] and focuses on the further study of the real-time digital-analog hybrid simulation in order to examine the possibility for implementing microprocessor-based autopilot .

This paper is organized as follows . A new adaptive controller based on conventional autopilot combined with feedforward controller is derived in Section II , and its real-time simulation configuration and software is developed in Section III . Simulation results are given and compared with those of all digital simulation and some key problems encountered in real-time control are discussed in detail in Section .

Finally , some conclusions are drawn .

II. THE DERIVATION OF THE ADAPTIVE LAW

The midcourse air-to-air missile autopilot actually are a ninth order complicated system . It's difficult to derive the adaptive law . Thus , the convenient way to solve this problem is that any conventional accelerometer flight control system (FCS) shown in Fig. 1 can be simplified as a second order , time-varying linear plant using fast reduction order method [7] , in order to easily derive the adaptive law based on the Lyapunov second method of MRAC . However , to approach the real situation , actual high order flight control system considering dynamics of the actuator , rate gyro and accelerometer combined with the above adaptive controller are used in the all digital simulations instead of simplified second model used above . So the simplified plant can be described as follows

$$\ddot{X}p + A1\cdot\dot{X}p + A2\cdot Xp = Kp\cdot U1 \qquad (1)$$

where : A1 , A2 , Kp are functions of the altitude H and speed V of the flight . The reference model which presents the desired performance of the flight trajectories is defined as

$$\ddot{X}m + Cm\cdot\dot{X}m + Dm\cdot Xm = Rm\cdot U0 \qquad (2)$$

and the generalized error E is

$$E = Xm - Xp \qquad (3)$$

In order to guarantee the error to approach zero , the synthetic adaptation signal U1 should compensate for the changes of the plant parameters . That is

$$U1 = Kv\cdot U0 + Ka\cdot Xp + Kr\cdot Xp \qquad (4)$$

where : Kv , Ka , Kr are adjustable parameters of the adaptive signal . From equations (1) - (4) ,we obtain the following error differential equation .

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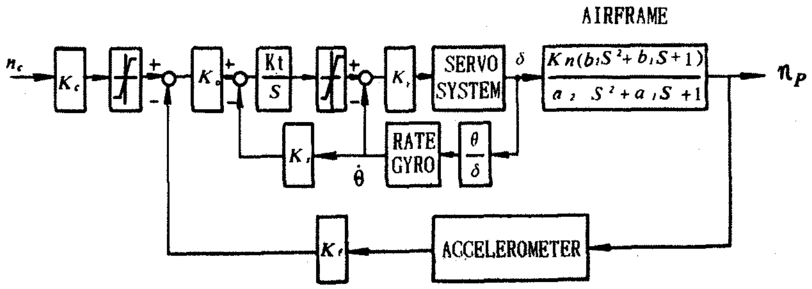


Fig. 1 The Conventional Flight Control System

$$\ddot{E} + Cm\cdot\dot{E} + Dm\cdot E = (Km - Kp\cdot Kf - Kp\cdot Kf\cdot Kv)\cdot U0$$
$$+ (A2 + Kp\cdot Kf - Dm - Kp\cdot Kf\cdot Ka)\cdot Xp$$
$$+ (A1 + Kp\cdot Kf - Cm - Kp\cdot Kf\cdot Kr)\cdot\dot{X}p$$
$$= \sum_{i=1}^{3} Xi\cdot Gi \qquad (5)$$

where :

$$X1 = Km - Kp\cdot Kf - Kp\cdot Kf\cdot Kv \qquad G1 = U0$$
$$X2 = A2 + Kp\cdot Kf - Dm - Kp\cdot Kf\cdot Ka \qquad G2 = Xp \qquad (6)$$
$$X3 = A1 + Kp\cdot Kf - Cm - Kp\cdot Kf\cdot Kr \qquad G3 = \dot{X}p$$

Finally , the error equation becomes

$$E + Cm\cdot\dot{E} + Dm\cdot E = \sum_{i=1}^{3} Xi\cdot Gi \qquad (7)$$

In order to derive the adaptive law , A Lyapunov function is chosen as

$$V = \dot{E}^2 + \sum_{i=1}^{3}(Xi + Ci\cdot\dot{E}\cdot Gi)^2 / Bi + Dm\cdot E^2 \qquad (8)$$

where : Bi , Ci are arbitrary positive constants , i = 1 , 2 , 3 . The derivative of Lyapunov function

$$\dot{V} = 2\,\dot{E}\left[\sum_{i=1}^{3} Xi\cdot Gi - Cm\cdot\dot{E} - Dm\cdot E \right] + 2\,Dm\cdot\dot{E}\cdot E$$
$$+ 2\sum_{i=1}^{3} (Xi + Ci\cdot\dot{E}\cdot Gi) / Bi$$
$$\cdot\left[\dot{X}i + Ci\frac{d}{dt}(\dot{E}\cdot Gi) \right]. \qquad (9)$$

is required to be negative to guarantee the stability of the system . We obtain

$$\dot{X}i = -Bi\cdot\dot{E}\cdot Gi - Ci\cdot\frac{d}{dt}(\dot{E}\cdot Gi) \qquad (10)$$

Substituting eq. (10) into eq. (9) , $\dot{V}$ becomes

$$\dot{V} = -2\,Cm\cdot(\dot{E})^2 - 2\,(\dot{E})^2\cdot\sum_{i=1}^{3} Ci\cdot Gi^2 < 0$$

From eq. (10) , we have

$$Kv = B1\int_{t_0}^{t}\dot{E}\cdot U0\cdot dt + C1\cdot\dot{E}\cdot U0 + Kv0$$
$$Ka = B2\int_{t_0}^{t}\dot{E}\cdot Xp\cdot dt + C2\cdot\dot{E}\cdot Xp + Ka0 \qquad (11)$$
$$Kr = B3\int_{t_0}^{t}\dot{E}\cdot Xp\cdot dt + C3\cdot\dot{E}\cdot Xp + Kr0$$

where : Kv0 , Ka0 , Kr0 are optimal values of conventional flight control system . They can be selected to make V(0,0) equal zero . Xp and $\dot{X}p$ are normal acceleration and its derivative of the missile . A linear compensator is used to make linear block of equivalent Popov feedback system be positive real .

$$Ef = \frac{D0+D1\cdot S}{1+Tf\cdot S}\cdot E$$

It's apparent that derivative of the normal acceleration is difficult to measure in the actual autopilot . But we can approximately use the pitch altitude rate of the missile to replace Xp according to the following equation .

$$\dot{N}p + R(t)\cdot Np = S(t)\cdot\dot{\theta}$$

where : $Np = Xp \quad \dot{N}p = \dot{X}p$

The block diagram of the adaptive control system is shown in figure 2 . the difference between Fig. 2 and Fig. 1 is that three constant parameters Kv , Ka and Kr in Fig. 1 are replaced by three adjustable ones . When something is wrong with the adaptive mechanism due to certain reasons , the conventional flight control system still works well because of the introduction of the conventional optimal values Kr(0), Ka(0) and Kv(0) .

It's seen from the all digital simulation that if only the above three adjustable parameters are used in the actual control system , a large over shoot will occur ,especially when using the second order actuator model . Thus , a feedforward adjustable gain Kt shown in Fig. 1 is introduced to overcome the effect of high frequency unmodelled error on the system . It's well known that the change of Kt affects the damping ratio of the system [8] . For this reason , Kt is then selected as feedforward adjustable parameter replacing adjustable parameter Kr without the destruction of the stability of the system .

The all digital simulations are made for several cases such as the effect of the noises , random disturbance and gust wind . It's seen from simulations that in the case of the selected reference model and adjustable parameters of the adaptive controller , each trajectory performance is greatly improved and all the specifications are satisfied using only a set of adaptive constants Bi and Ci (i = 1 , 2 , 3) and also shows that the performance of the adaptive control based on the conventional flight control system is much superior to that of the conventional FCS only or that of the adaptive controller only .

III DIGITAL-ANALOG SIMULATION

The real-time hybrid simulation is a key step for

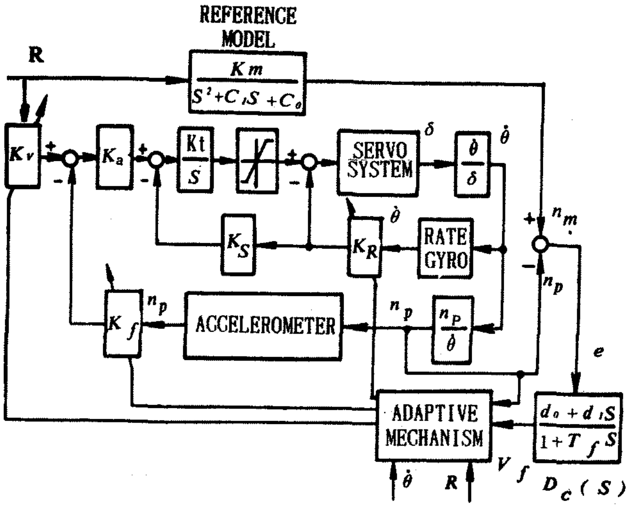


Fig. 2 The Adaptive Flight Control System

implementing microprocessor-based adaptive control system . Based on the all digital simulation , a laboratory real-time simulation configuration with a microcomputer IBM PC/XT , coprocessor 8087 and a general-purpose interface card LAB-MASTER including DADIO and its software package were developed . The hybrid simulation hardware configuration is shown in Fig. 3 [9] .

The novel features of this approach are

(1) The motive we develop this configuration is that interfacing can be made much easier by using two simple concepts : firstly, buy a commercially available hardware where possible ; secondly , develop a general purpose software that can be used for almost any project without the need of the modification of the main program and some subroutines .

(2) High speed coprocessor 8087 was selected to implement the adaptive controller . It has hardware multiplication instructions which only take 19 μs . In this way , the whole program is much easier to develop and easy to read .

(3) The whole software programming consists of two parts . The main program is edited in FORTRAN language and the adaptive subroutine uses 80-bit floating-point calculations . Some instructions such as A/D convertion instruction ADMXST , D/A convertion instruction DAC and timing instruction TIMRD etc . PAC software subroutines are called by the main program . It is flexible and convenient to use hybrid languages in the real-time simulation [10] [11] .

The digital-analog hybrid simulation block diagram is shown in Fig. 4 . The analog computer is used to model a time-varying missile body dynamics . Five-channel analog inputs the reference input U0 , the reference model output Nm , the missile's normal acceleration Np , and the medium signals F1 and F2 are converted into digital signals respectively through A/D converters , and three-channel digital outputs Ka·Np , Kv·F1 and Kt·F2 are transformed into analog control signals through D/A converters to control the actuator . As described in Section II , P+I algorithm is used to implement microprocessor-based adaptive controller . The analog adaptive algorithm can be transformed into difference equation format through bilinear transform as shown in Fig.5.But the reference model can also be implemented by using digital computer or analog computer . The real-time FCS flow chart and link/load functional block diagram are shown in Fig. 6 and Fig. 7 respectively . A sampling period Ts of 5 msec is chosen due to 4.2 msec computational delay . As shown in Fig. 6 ,after the digital computer starts , the adaptive constants Bi , Ci are read into the data file .The sampling period Ts is put into computer through keyboard in man-machine communication way , and then the timer t is started with PAC software . A/D converter is inverted by using PAC software instructions , and the adaptive algorithm subroutine ADAPT. is called . Note that a limiter should be introduced after ADAPT. .

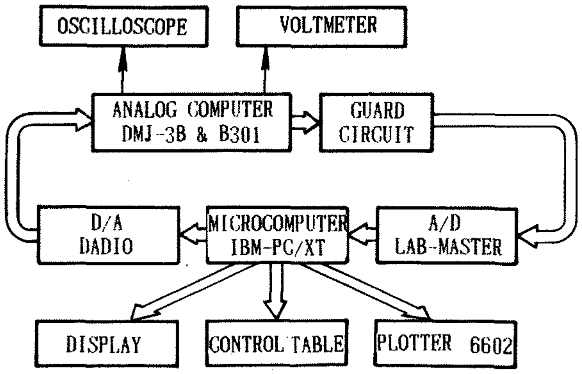


Fig. 3 Hybrid Simulation Hardware Configuration

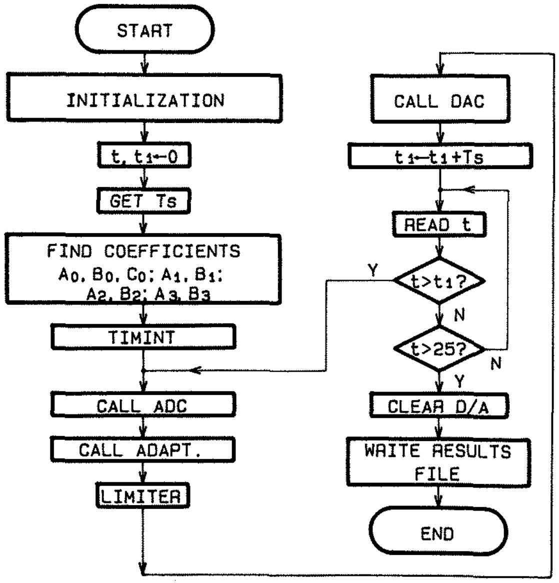


Fig. 6 Flow Chart of the Main Program

The real-time hybrid simulations were made for different trajectories . The same results as those of

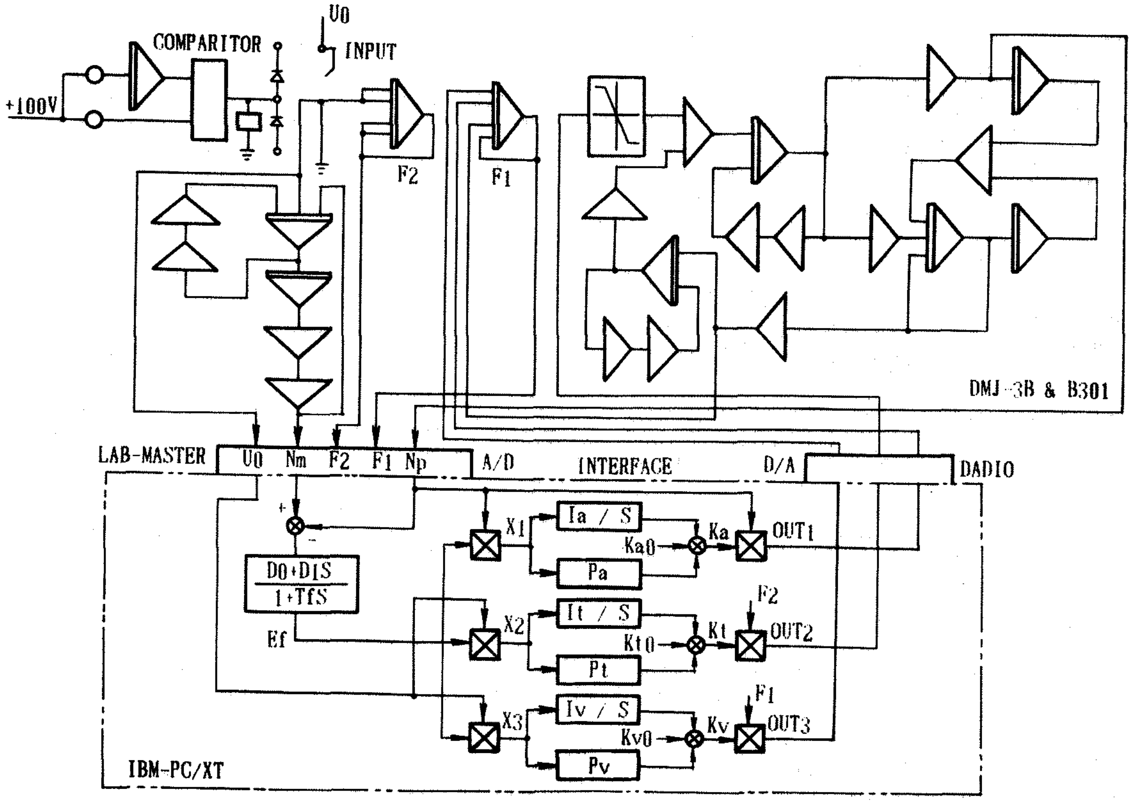


Fig. 4 Hybrid Simulation Block Diagram

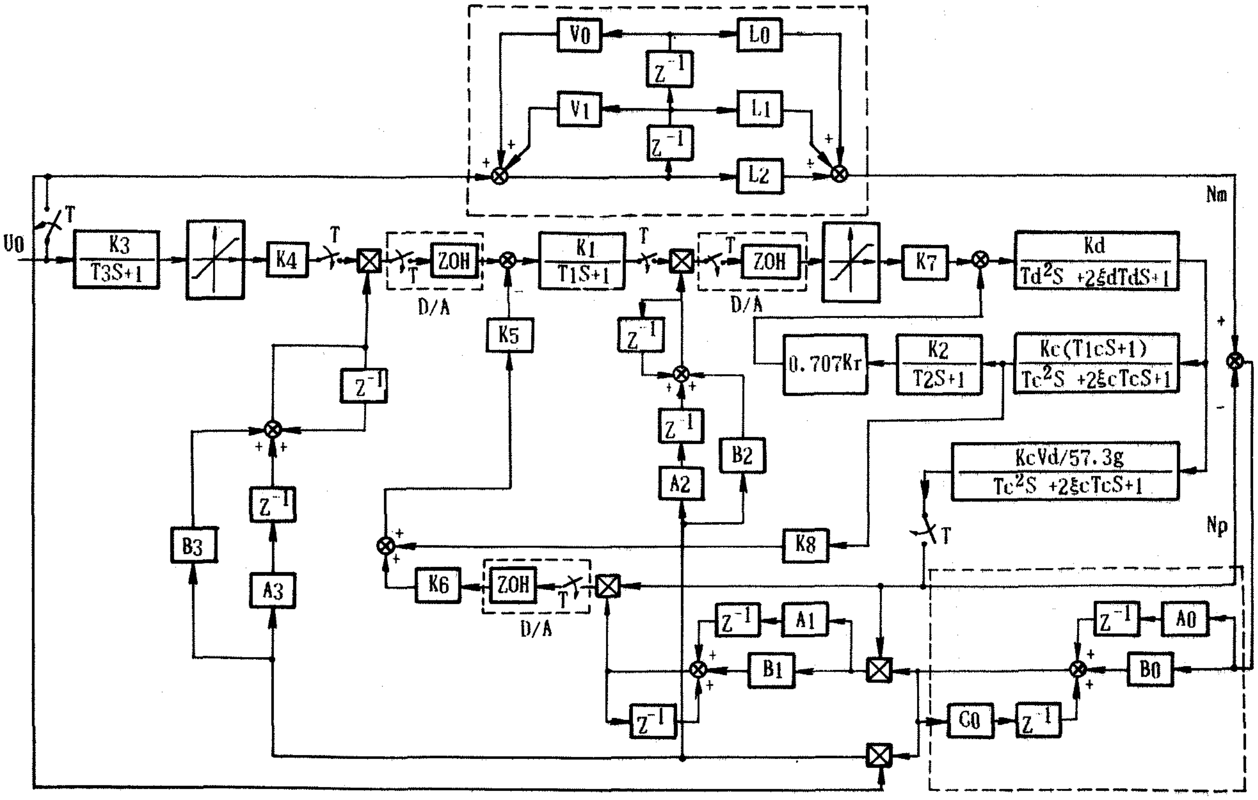


Fig. 5 The Data Sampling Control System

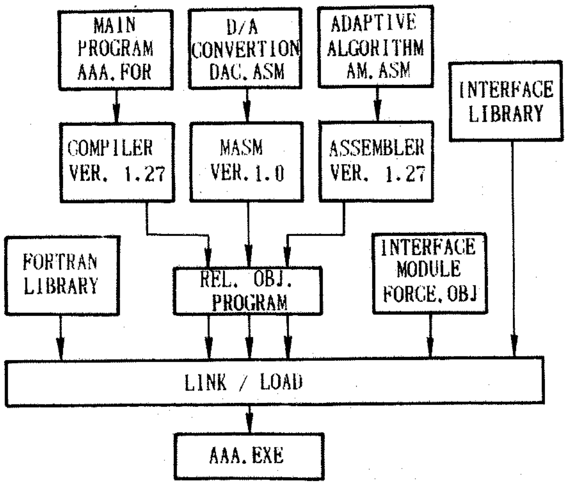
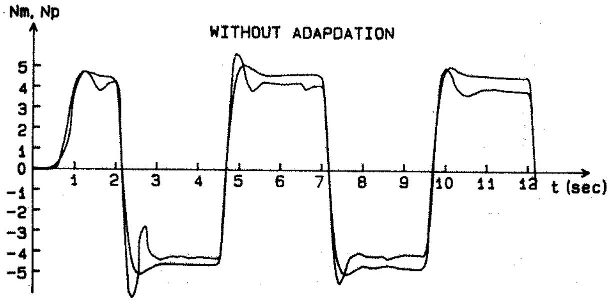
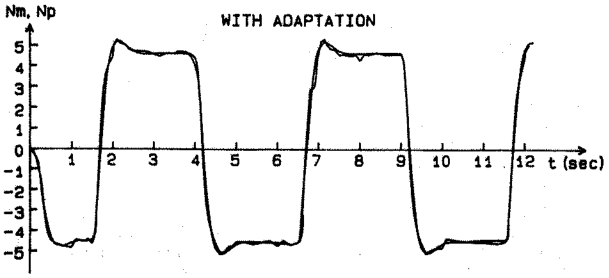


Fig. 7 Programs LINK/LOAD Functional Block Diagram

the all digital simulations were obtained as shown in Fig. 8 . From the comparison of the adaptive control with the conventional control , it is also seen that the system performance due to the introduction of the adaptive controller is greatly improved . In addition, the optimal behavior for all the trajectories was obtained by using only a set of adaptive constants .



a . System Response for the Conventional Autopilot



b . System Response for the Adaptive Autopilot

Fig. 8 System Responses

IV SOME IMPLEMENTATION CONSIDERATIONS

The operation of the adaptive FCS in view of aspect connected with its practical implementation has been investigated by digital-analog simulation . In particular , the following points have been studied .

(1) The effect of model order uncertainty
The study on unmodelled error of the plant is an important problem in real-time simulation , since the actuator and the plant are assumed certain models , which in practice constitute an approximation . In order to check this effect by digital-analog simulation , an extra pole has been added. to the controlled plant , while the reference model remains second order . The extra pole can represent a short time constant of the actuator system , neglected in the preliminary analysis . Introducing this extra pole does not significantly change the dynamic response of digital adaptive FCS as shown in Fig. 9 . The system still asymptotically follows reference model very well .

(2) The effect of the sampling rate
The selection of the sampling rate in the design of the digital adaptive autopilot based on sampled-data control system theory is important since it affects autopilot stability and influences the computation speed of the processor . By considering the sampling rate , allowable transport lag , and total number of computations to be performed , the processor speed requirement can be determined . Generally speaking , it is expected that a relatively high sampling rate is required in an autopilot for tactical missile to guarantee the performance and dynamic stability . The input frequency region of interest for autopilot rigid body stability is from zero to ten HZ . The additional phase shift caused by hold and transport lag should be no greater than 10 degrees [2] . Considering the above requirements , we select a 5 msec of sampling period in the real-time simulation using 8087 coprocessor .The better results were obtained as shown in Fig. 10 . The next step in this project would be the actual implementation of the adaptive control algorithm . No doult , the powerful 16-bit single chip microcomputer such as Intel 8096 , Motorola 68200 , NEC μp 78312 will be used for developing products instead of the current microcomputers .

(3) The effect of large input signal
It's seen from simulation that the adaptive FCS can be unstable for large values of reference input . If the input magnitude is smaller , the system behavior becomes worse . The best way to solve this problem is that a weighting factor which is a function of input magnitude is used to replace the adaptive constants Bi and Ci of the adaptive algorithm .

(4) The adaptive controller based on the conventional FCS we developed in this project is much better than other adaptive configurations . Firstly , the robustness of the system is obtained through the conventional FCS ; Secondly , when the adaptive mechanism does not work , the conventional autopilot still works to guarantee the reliability of the system . The worst performance of the system is kept to the level of the conventional FCS without the adaptive controller . So it is sometimes advantageous to combine an adaptive controller with nonadaptive controller when implementing the final control law

(e.g. by implementing an adaptive controller around an existing conventional controller) [12] .

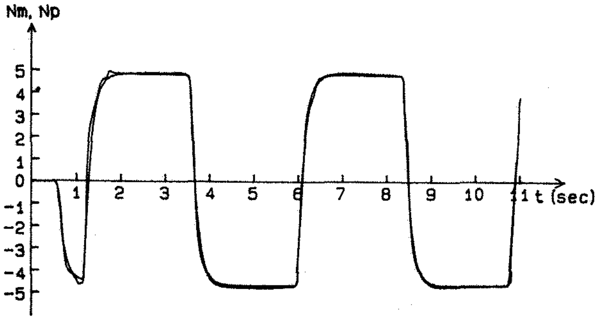
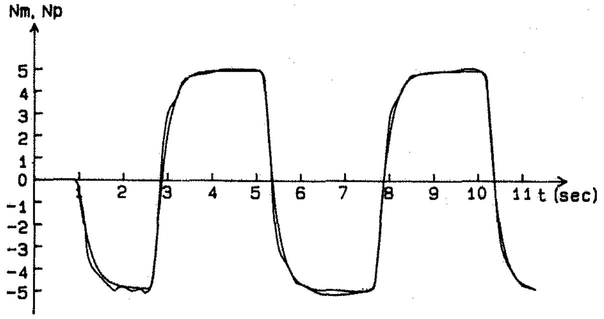
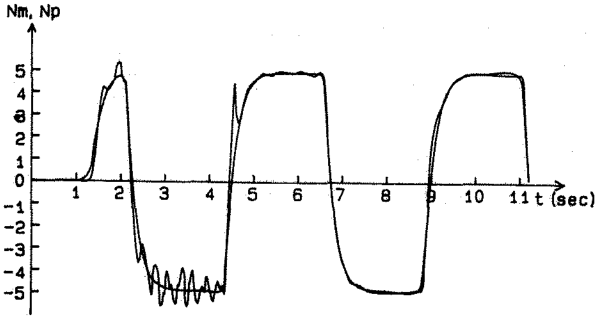


Fig. 9 System Response with a Extra Pole Added



a. Ts = 10 msec



b . Ts = 28 msec

Fig. 10 The Effect of Sampling Period

V CONCLUSIONS

A new kind of digital adaptive law based on the conventional FCS for a tactical missile has been developed . A laboratory general-purpose , real-time simulation configuration and its software package are outlined in this paper . By comparing its behavior with that of the conventional FCS , we obtained the excellent performance using this adaptive law not only in the all digital simulation but also in the digital-analog hybrid simulation . The digital-analog hybrid simulation configuration we developed here represents a versatile hardware and software combination and a simple , cost effective , easy to use tool for the study of real-time control both in the aviation industry and in a wide variety of commonly encountered industry projects .

It's therefore predicted that owing to the high development of VHSIC , digital adaptive autopilot will soon be applied to the next generation of tactical weapons .

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