Model Reference Adaptive Speed Control of a DC Motor Drive

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ABSTRACT

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Adaptive control has been extensively used in various industrial applications. Due to the advancing microprocessor technology, these control methods can now be applied to drive speed control. The main advantage of adaptive control is its insensitivity to the variation of process parameters. The state space representation of a motor and its mechanical load is developed. A model reference adaptive control system using the direct approach is proposed.
The adaptive control parameters are calculated based on the requirement of a typical speed response which could be required in a typical drive application. The same motor and mechanical system is simulated using the proposed adaptive control method and a PID control loop to evaluate the performance of the adaptive control system versus the PID loop.

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In today's competitive world it is extremely important that technology be a main part of the government and company's future development plans. It is not enough to talk about employee's development and better working atmosphere; it is time that the employees become part of the team and their future development be important and considered a part of the company's and government plans. Training and employee development should be done at all levels not only at the higher management levels.

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1. INTRODUCTION

Variable speed motor drive applications are finding their place in areas of the industrial and commercial sectors of the economy which had been previously impractical. This has been due to an increasing awareness of energy conservation, increasing quality requirements and increasing production efficiencies in the various production processes.

The push towards new drive applications has not only originated from the end user but also from the new technologies which are also revolutionizing the design and manufacture of AC and DC drives. This momentum has spurred the evolution of new drive applications in which the end customer is able to apply new and more efficient drive products as well as being able to purchase them at lower prices with higher performance characteristics.

Although there is ongoing improvements in the power components used in the drives, the major efforts are being placed in providing customers more powerful products through the use of new and more powerful microprocessor technology. This will benefit the end customer through improved troubleshooting techniques, improved man machine communications and finally improvement of the drive control techniques of speed and current which will provide an overall improvement of the end product quality and production efficiencies.

This thesis will concentrate its discussion on a speed control technique called adaptive control, which has been discussed intensely in applications such as flight control, robot movement control as well as some process control,etc. Technical papers have discussed various types of adaptive control for drives as well but with little effect on the control strategies used by drive manufacturers due to the complexity and high processor capacity requirement of this type of control. The use of today's ever so developing microprocessor technology is in the process of converting the classical control methods used in drives presently to adaptive control methods.

1.1 ISSUES TO BE COVERED

This thesis will investigate a stable adaptive speed control of a DC motor using the model reference approach described in [2]. The new and more powerful microprocessors are making it possible to implement these advanced control techniques.

It will be shown through the use of simulation that this type of technique will provide a better quality of speed control throughout the life of the system and that the control quality can be maintained without having to retune the system due to changes in either the load or motor characteristics.

It will be shown, through simulation, that the dynamic performance of the system can be equivalent to or better than a typical drive using a classical approach to speed control and that control stability will no longer be affected by system parameter changes in the plant.

1.2 DC DRIVES AND THEIR MARKET STATUS

The DC drive has seen a decrease in its market share of the drive market due to the following reasons:

- AC drives becoming more competitive along with the ruggedness of the AC motor.
- The DC motor provides greater maintenance problems than its AC counterpart.
- The AC drive has been developed to the point that it can give the same performance as the DC drive in many applications.
- The DC motor is more expensive than its AC counterpart.
- The DC drive is known to provide a greater amount of line harmonics than some of the AC drive technologies presently available in the market.

Whether the above reasons are justified or not, the DC drive market share is expected to drop due to a major marketing effort by the various manufacturers of AC drives.

In order to regain or maintain its market share, the DC system must provide the end user with clear advantages and must reduce its problem areas. The area of drive control accuracy and the versatility of the DC motor is one area where the customer can benefit through the use of adaptive control in DC drives.

This thesis will not discuss the benefits of the AC drives versus DC drives but will discuss a speed control method which will provide the end customer with an improved control; nor will this thesis deny that the same control technique cannot be used on AC drives although the complexity would be greater in the AC drive applications. The proposed technique can be applied in many various applications, although the greater the order of the system the more complex the set of differential equations will be. As well the parameter and gain settings tend to increase in difficulty with a greater number of differential state equations.

One major element in the DC drive system is the DC motor. In order to demonstrate the effectiveness of the DC drive, further improvement will have to be made on the DC motor design to counteract the disadvantages as compared to the AC motor. These developments will have to improve the motor operation and reduce the operating cost of the motor.

None of the above subjects will be discussed but it is crucial that researchers and companies realize that customers require much more than the possibilities that new powerful technologies can bring them.

1.3 SYSTEM DESCRIPTION FOR THE DC DRIVE

The system which is analyzed, shown in Fig. 1, has been based on the one used in [3] and therefore has the same parameters.

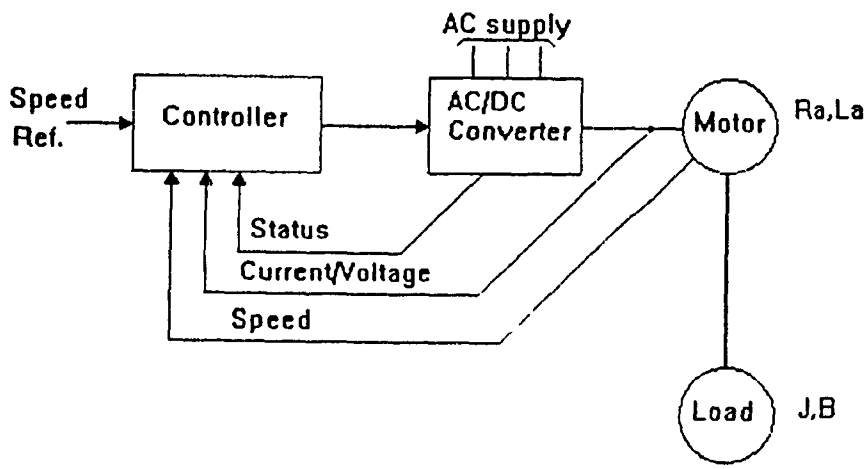

Fig. 1: Functional block diagram of a motor drive

The system consists of the following components:

- A six pulse thyristor controlled AC/DC converter and control software
- A DC motor
- A gear reducer and a mechanical load

The DC motor is a separately excited machine. The speed control which is considered in this paper is through the armature with the field current being constant.

The drive control system consists of a combination of boards which interface to the analog components of the drive as well as the customer; this basically means that the drive control is completely digitally controlled. The drive software would be required to accomplish the following tasks:

- Provide a digital current control loop
- Provide a digital adaptive speed control loop
- Turn on sequence control of the power supplies, fans, contactors etc.
- Protection of both motor and converter
- Provide a reliable and user friendly man-machine communication

1.4 DC MOTOR SPEED CONTROL

This section will establish the plant equations which consists of the motor and its associated mechanical load. From these basic equations a state space representation will be defined for the system which is used for the adaptive control.

In order to accomplish this, the following assumptions were made:

1. The DC motor and its mechanical load has been assumed to be a second order system
2. The disturbance torque T_1 is assumed to be zero
3. The motor and mechanical load start from rest

The block diagram of a DC motor is shown in Fig. 2 and the equations which determine the operation are shown below:

$$V_a = E_g + R_a I_a + L_a \dot{I}_a \qquad (1)$$

$$T = T_1 + BN + J\dot{N} \qquad (2)$$

$$E_g = K_a \Phi N \qquad (3)$$

$$T = K_a \Phi I_a \qquad (4)$$

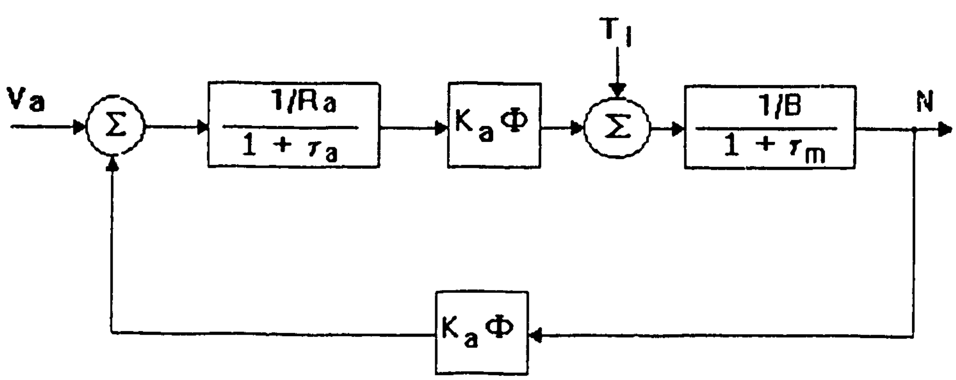

Fig. 2:Equivalent block diagram of a motor and load

By transforming the above equations into the s-domain and substituting for I_a, the motor equations can be reduced to one equation as shown below in Eq. 5. The detailed derivation of this equation is found in [1].

$$V_a(s) = (K_a\phi + \frac{R_a B}{K_a\Phi})N(s) + (\frac{L_a B}{K_a\Phi} + \frac{R_a J}{K_a\Phi})sN(s) + \frac{L_a J}{K_a\Phi}s^2 N(s) \tag{5}$$

The variables used in the above equations are defined as follows:

R_a = DC motor armature resistance = 1.16 ohms

$K_a\Phi$ = Motor constant = 0.66V/rad/sec

τ_e = electrical time constant = 0.052 sec =La/Ra

J = system inertia = 0.023 kg·m

B = Viscous-friction coefficient = 0.018 N·m/rad/sec

τ_m =mechanical time constant = 1.28 sec = J/B

Converting back to the time domain the following differential equation results:

$$V_a(t) = (K_a\phi + \frac{R_a B}{K_a\Phi})n(t) + (\frac{L_a B}{K_a\Phi} + \frac{R_a J}{K_a\Phi})\dot{n}(t) + \frac{L_a J}{K_a\Phi}\ddot{n}(t) \tag{6}$$

Defining the variables $x_1(t)$ and $x_2(t)$ as

$$\begin{aligned} x_1(t) &= n(t) = \text{motor actual speed} \\ x_2(t) &= \dot{n}(t) = \text{motor actual acceleration} \end{aligned} \tag{7}$$

and then replacing them in equation (6) we obtain

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2(t) &= -\frac{K_a\Phi}{L_aJ}\left(K_a\Phi+\frac{R_aB}{K_a\Phi}\right)x_1(t) - \frac{K_a\Phi}{L_aJ}\left(\frac{L_aB}{K_a\Phi}+\frac{R_aJ}{K_a\Phi}\right)x_2(t) \\ &\quad + \frac{K_a\Phi}{L_aJ}V_a(t) \end{aligned} \tag{8}$$

The above equations can be put into a compact matrix form as follows:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\dfrac{(K_a\Phi)^2+(R_aB)}{L_aJ} & -\dfrac{B}{J}-\dfrac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{K_a\Phi}{L_aJ} \end{bmatrix} V_a(t) \tag{9}$$

which is equivalent to

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{10}$$

where the matrices are as defined below:

$$x = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \tag{11}$$

$$A = \begin{bmatrix} 0 & 1 \\ -\dfrac{(K_a\Phi)^2+(R_aB)}{L_aJ} & -\dfrac{B}{J}-\dfrac{R_a}{L_a} \end{bmatrix} \tag{12}$$

$$B = \begin{bmatrix} 0 \\ \dfrac{K_a\Phi}{L_aB} \end{bmatrix} \tag{13}$$

By substituting for the plant parameters as defined previously into the state equation 9 above we obtain:

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}0 & 1\\ -328.46 & -20.01\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix} + \begin{bmatrix}0\\ 474.9\end{bmatrix} V_a(t) \tag{14}$$

2. DISCUSSION OF VARIOUS CONTROL METHODS

The following sections will review some of the control methods which could possibly be used with motor drives. Both conventional methods as well as adaptive methods are discussed.

2.1 CONVENTIONAL FEEDBACK CONTROL

Conventional control methods using a PI or PID speed control have been the standard solution in motor drives and for many drive manufacturers is still today a standard and common method of motor speed control. The block diagram is shown in Fig. 3 below.

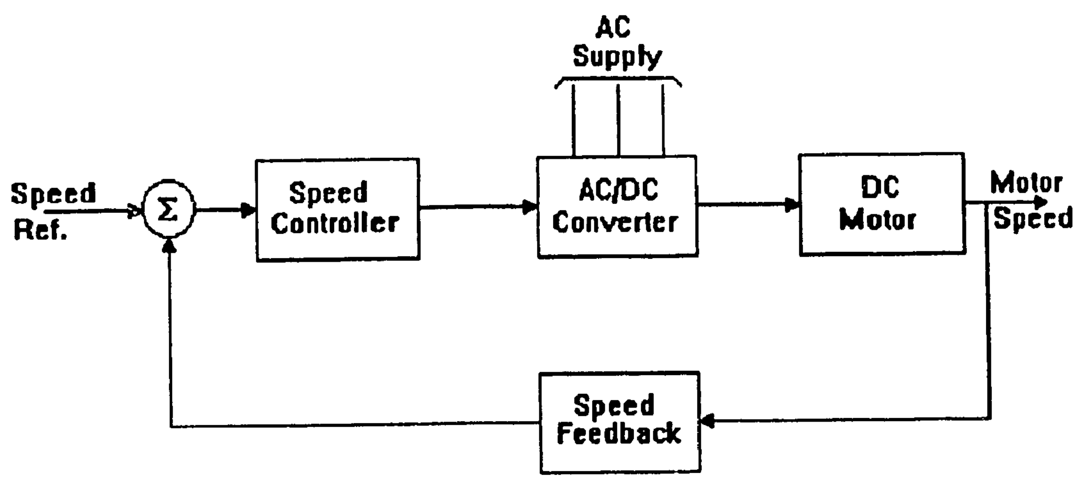

Fig. 3:Basic block diagram of a conventional speed control

This type of control is one which attempts to maintain a predetermined relationship between the output and the input reference by taking the error between these two values and then taking appropriate corrective action.

The use of feedback or closed loop control makes the system relatively insensitive to external or internal variation of the system parameters. The problems that are usually encountered with this type of control is that it does not take into account the deterioration of the system components as time goes on. If these changes are significant over a period of time then the control system will no longer perform properly. This type of control is extensively treated in both [1] and [4] and therefore will not be treated further in this thesis.

2.2 ADAPTIVE CONTROL

Adaptive control has been widely used in many industries such as aviation, robotics and chemicals. Due to the advances in microprocessor technology, the applications where adaptive control is used is steadily increasing.

The term "adapt" signifies to change its own behaviour so as to conform to new conditions. Therefore, an adaptive regulator can change its behaviour in response to changes in the parameters of the process or external disturbances. In this type of application which this thesis is concerned, these changes can occur from the following system elements:

1. DC motor parameters; for example the resistance or the inductance of the motor, field current etc.
2. The system inertia can also change with time due to gear backlash or usage of the various system components.
3. External disturbances from the process itself due to raw material changes.

With conventional control methods a change of parameters would require the retuning of the control loops. The adaptive control methods will eliminate this need.

In adaptive control methods there are basically two types of control methods: direct and indirect adaptive controllers. In direct adaptive control methods, the controller parameters are updated in order to improve a performance index. The plant parameters do not play a major role in the updating of the controller parameters. Whereas in indirect adaptive controllers the plant parameters are estimated on line and the control parameters are adjusted based on these estimates.

2.2.1 SELF TUNING REGULATORS

The block diagram of a self tuning regulator (STR) shown in Fig. 4 is made up of the following blocks: regulator, process, estimation and the design. The self tuning regulator consists of two loops where the inner loop is made up of the process and an ordinary linear feedback regulator.

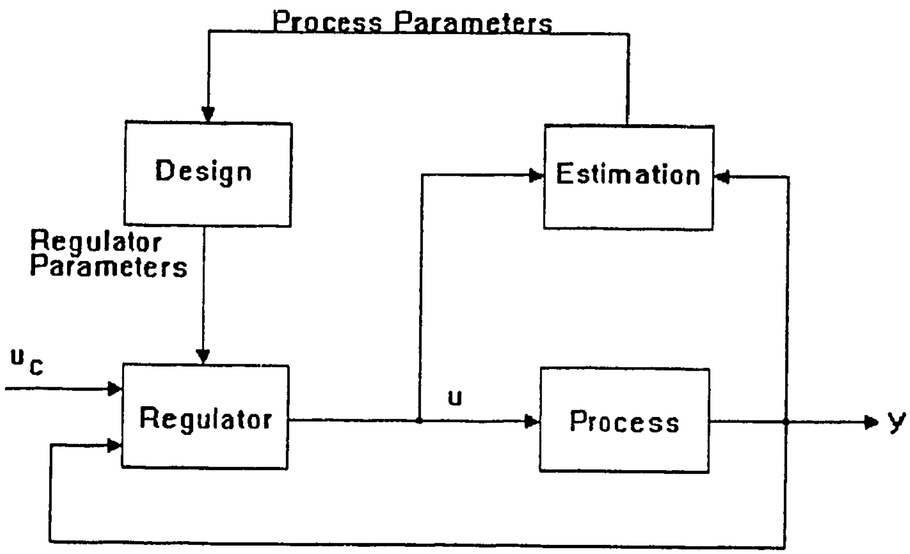

Fig. 4:Block diagram of a self-tuning regulator (STR)

The parameters of the regulator are adjusted by the outer loop which is made up of a recursive parameter estimator and a regulator.

2.2.2 GAIN SCHEDULING

Certain processes have auxiliary variables which can be measured and correspond closely to the dynamics of the process. As a result, these variables can be affected such that the parameters of the regulator can be changed to reduce the negative effects resulting from process parameter changes.

This type of control is called gain scheduling since the gain is changed to reduce the influences of the parameter variations which may occur in the system. The block diagram of a gain scheduling controller is shown below in Fig. 5. Gain scheduling has been used quite successfully for aircraft flight control systems and can be regarded as an open loop control since the gains are adjusted by feedforward compensation.

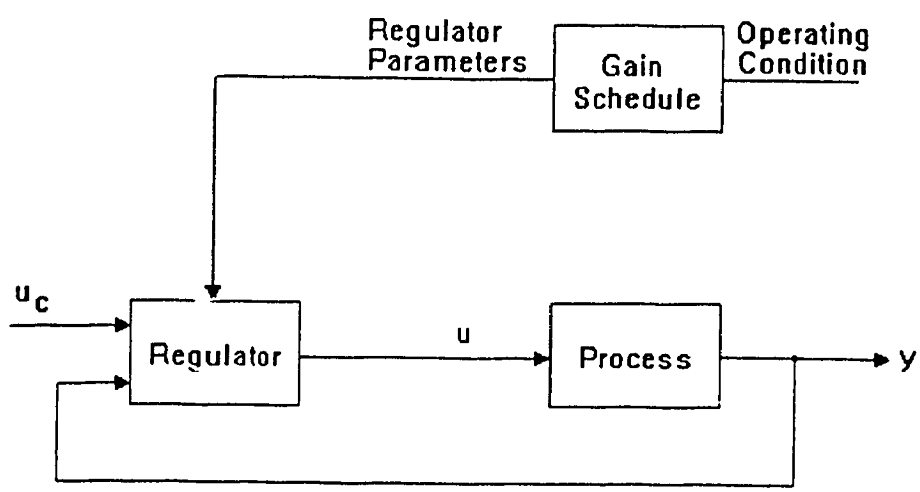

Fig. 5:Block diagram of a system with gain scheduling

In gain scheduling, a scheduling variable is first determined in one operating condition together with its corresponding process parameter and are stored in a table. The complete gain schedule is completed when measurements have been made throughout the whole operating range.
This type of control system does not measure the performance of the process and therefore has difficulty compensating for incorrect process performance.

2.2.3 AUTO TUNING

As previously discussed, some applications will perform satisfactorily with the use of conventional feedback control; although tuning of a conventional control loop can be tedious. In order to simplify the task of tuning the control loop, an adaptive control method called auto tuning can be used. This method will simplify and automate the tuning of the control loop thus reducing the commissioning time or start up after a period of downtime.

Auto-tuning is usually based on an experimental phase during the commissioning of these controllers in which some test signals such as steps or pulses are inputted into the system. The regulator parameters are then determined from these experiments. The advantage with automatic tuners is that the experiment is supervised by the appropriate personnel and therefore the required protections can then be simpler.

2.2.4 MODEL REFERENCE ADAPTIVE SYSTEMS

A model reference adaptive system essentially has an innner loop which forms part of a convential feedback control and an outer loop which adjusts the adaptive control parameters. The basic goal of this type of system is to make the plant behave in the same way as the model. A block diagram of the system is shown in Fig. 6. and the individual blocks are briefly described below:

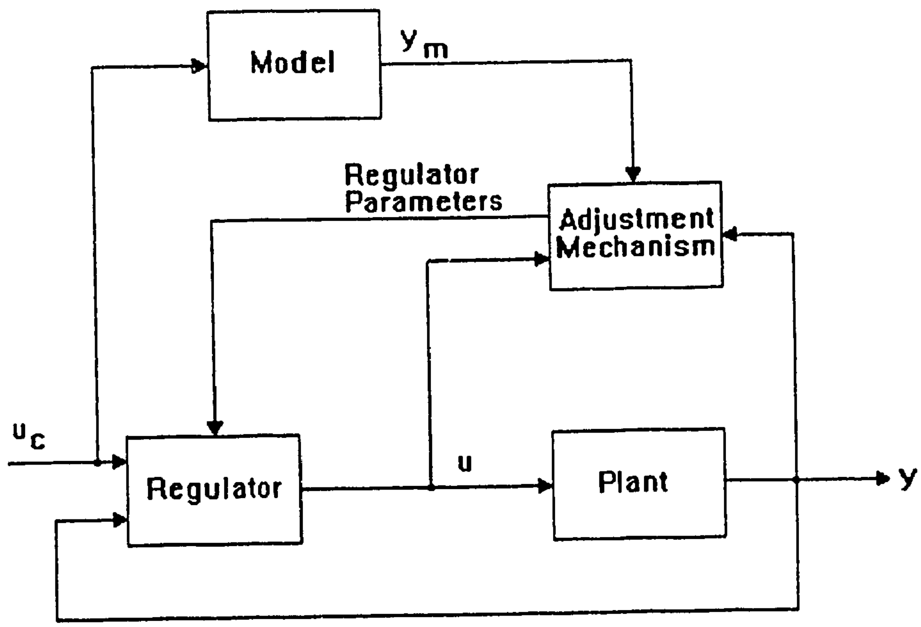

Fig. 6: Block diagram of a model reference adaptive system (MRAS)

1. The plant or process to be controlled.
2. The model of the plant which provide a reference as to the desired performance that the plant should have.
3. An adjustment mechanism which provides an output depending on the status of the actual plant output, the plant reference and the status of the model output.
4. A regulator which actually provides the plant with the reference.

By the use of mathematical models, it is possible to define the performance of the system by properly choosing the parameters of the model. The use of models assumes that the designer has a priori knowledge of the system under consideration. Although the model structures can be linear or non-linear, practical considerations as well as ease of analysis usually limits the models to linear time-invariant systems. The general form of a model following system is:

$$\dot{x}_m = A_m x_m + B_m r$$
$$y_m = C_m x_m \qquad (15)$$

where: A_m is a stable n by n matrix with constant elements

B_m, C_m are constant matrices of appropriate dimension

r is a piecewise-continuous uniformly bounded function

Given a plant defined as

$$\dot{x}_p = A_p x_p + B_p u$$
$$y_p = C_p x_p \qquad (16)$$

where: A_p is a stable n by n matrix with constant elements

B_p, C_p are constant matrices of appropriate dimension

u is a piecewise-continuous uniformly bounded function

y_p is the plant output which is speed in this case

the objective of the adaptive system would be to determine the signal u to the plant so that the output $y_p(t)$ approaches $y_m(t)$ as t approaches infinity. This would render the error to be zero as t approaches infinity.

2.3 LITERATURE REVIEW

The technical literature which has been written in recent years on control of motors has been concentrated on variable structure control(VSS) and sliding mode conrol which is a type of variable structure control.

In [10] it is suggested that sliding mode control will be an important area of research and application for the speed control of motors and drives. This is due to the fact of the simplicity of these types of controllers as compared to other types and that variable structure controllers can provide parameter insensitive features and predetermined error dynamics.

In [9] it is suggested that optimal sliding-mode control is insensitive to parameter variations and can achieve robust performance against external disturbances. However, the authors suggest that in order to eliminate the steady state error an integral controller is included in the overall system; therefore increasing the order of the system. In order to make the system robust,the following criteria is to be met:

1. The system must always be asymptotically stable and possess a fast response to a reference input. The performance is insensitive to system parameter variations.
2. The system must have low sensitivity to external disturbances. The authors state that the transient speed deviation under a sudden load application should be a minimum with a fast speed recovery.
3. There must be no steady-state error when the system is subject to an external disturbance or load variation.

The above requirements can be difficult to meet in most applications since the plant parameters are not always known.

In [11] a new VSS control algorithm called chattering alleviation control (CAC) is proposed. The authors state that the VSS control contains chattering about its switching surface. This therefore requires additional control effort and may excite unmodeled dynamics in the system.

In [12] a new design of the variable structure control to alleviate the chattering level problem associated with variable structure control is proposed. The method proposed uses an improved chattering alleviation control augmented with a boundary layer. It is suggested that this new method results in the following advantages while at the same time preserving the features of CAC control:

1. The control function becomes linear.
2. The resulting chattering level is smaller than that of a standard chattering alleviation control (CAC).
3. The parameters in the traditional boundary layer approach can be determined quantitatively.
4. The new system is proven to be asymptotically stable.
5. The applied motor armature voltage contains reduced higher frequency harmonics as compared to other types of variable structure controllers.

In [14] an advanced position control for the use with industrial electrical drives is discussed.The authors propose to use a recursive least squares algorithm (RLS algorithm) for the speed control and a pole assignment algorithm for the updating of the controller parameters. The position control would be accomplished by a time optimal and quasi time optimal adaptive control. The RLS algorithm was chosen for the on line identification, the pole assignment algorithm for the speed control and a non-linear adaptive controller for the time optimal position control loop.It is stated that in order to insure a good transient response, the identification and adaptation of the controller must be executed as fast as possible although no specification of the time is given.This technique also requires periodic excitation of the controls, otherwise faulty identification can result. Under stationary conditions no adaptation is carried out since the parameters cannot be improved without excitation. Significant changes in the input and output have to be of a certain magnitude in order to refresh the system parameters, although specific values are not mentioned. Therefore, this system requires many conditions in order for the controller to perform as specified. Furthermore, this technique is a combination of different adaptive methods which complicates the practical implementation.

In [15] a sliding mode controller for sensorless control of position and velocity for a brushless DC motor, which is insensitive to disturbances, is discussed. The switching signals of the sliding mode contain the induced voltages of the motors making it possible to obtain the position and velocity from the switching signals. Due to the heavy contamination of the switching signals, an adaptive scheme for the robust estimation of the velocity of the motor is also proposed.

In [16] an adaptive pole placement controller for positioning control for a DC drive in a robotic application is proposed. In order to improve the performance of the controller, the model of the motor takes into account the effects of the resistance torque. The complexity of the identification algorithm can grow significantly as the number of parameters increase and as a result, it is suggested that a continuous on-line identification procedure is used when large variations in the system parameters are expected. This of course will complicate the controller design and implementation.

In [22] a model reference control is proposed for AC drive speed control. The proposed algorithm contains conventional PI control for filtering the speed error. A limitation is placed on the model inertia parameter such that it is set to a worst case condition. Therefore, the speed response may not be optimum.

In [23] a model reference adaptive controller of the linear model following controller type (LMFC) is proposed for the speed control of a DC drive. The proposed model is a first order system. The compensation gains are modified according to the estimations of the plant parameters. As a result, the proposed system is of the indirect adaptive control type. A PI regulator is also used at the input to provide a better control performance fo this proposed method.

2.4 ITEMS OF CONCERN WITH THE ADAPTIVE CONTROL METHODS

The above references discuss various adaptive control techniques for drive applications. Although these techniques have been proven in other industrial applications they may cause problems or complicate the practical implementation of these methods in some sensitive applications such as pulp and paper or steel. Below are some critiques of the above methods.

2.4.1 VARIABLE STRUCTURE CONTROL

VSS control systems are a special class of adaptive relay controls in which the term variable signifies that the structure may be changed by changing the feedback gain depending on the status of the control system variables. This type of control has been discussed in [9,10,11,12] and [15]. This adaptive control method has received a great deal of attention for drive applications.

All the references quoted above state that these types of adaptive systems provide the possibility of making the system insensitive to process dynamic variations and they can provide control robustness. But these adaptive systems are difficult to design for practical application when operated in varying conditions. Some of the problems are listed below:

1. The choice of the switching plane may be a complicated procedure in the event of the plant dynamics not being fully understood or varying due to process changes. Typical examples might be varying grades of paper in the pulp and paper applications or varying steel products in the steel industry.
2. It is a well known fact that chattering is one of the characteristics of VSS controls. Even though some of the references provide solutions to diminish this drawback, chattering can provide problems to sensitive and high accuracy applications.
3. Switching frequencies for chattering control must be high for accurate control. This would require components which are rated for this duty and increased losses would result.

4. It is imperative in this type of control that the sliding mode is reached. With the process dynamics changing after a period of time, this would be more difficult. Different products would result in varying dynamics.

2.4.2 POLE PLACEMENT DESIGN

Pole placement design is one of the common and well know direct design techniques which is proposed in [5]. But again there are some very important concerns when applied in standard industrial applications. Below are some of the concerns:

1. This type of controller is simpler to design as compared to other types of adaptive controllers, but its use becomes questionable when applied with plants which have varying products.
   The parameters are entered for a known set of conditions, if these change then the control can no longer perform.
2. The pole placement design procedure is to find a feedback law such that the closed loop poles have the desired location. This feedback law may be difficult to define in cases where the plant parameters change.

3. A good knowledge of the system is required when using this type of controller. Therefore if the process data is not accurate or varying, then the control will be inaccurate. The design parameters have a direct influence on the closed loop performance.

2.4.3 COMPETITIVE MRAC SYSTEMS

The model reference adaptive controls discussed above have the disadvantage of the basic model being a first order system while at the same time requiring the use of a PI control to insure the correct response of either the control parameters or the input reference. This limits the performance of the control method while not taking advantage of the benefits of adaptive control techniques.

2.5 DISCUSSION OF THE PROPOSED METHOD

The adaptive control method which is proposed in this thesis is based on [2]. This paper discusses only the direct control method of adaptive control where the parameters are adjusted without the intermediate identification stage. It is assumed that the plant has the following properties:

$$W_p(s) = h^T(sI-A_p)^{-1}b_p = \frac{k_p Z_p(s)}{R_p(s)} \qquad (17)$$

where $W_p(s)$ is strictly proper

$Z_p(s)$ is monic Hurwitz polymonial of degree $m \leq n-1$

$R_p(s)$ is a monic polynomial of degree n

k_p is a constant gain parameter

It is further assumed that m,n and the sign of k_p are known and is assumed to be positive.

The model has the following transfer function with the conditions defined below:

$$W_m(s) = \frac{k_m Z_m(s)}{R_m(s)} \tag{18}$$

Where $Z_m(s)$ is a monic Hurwitz polynomial of degree $r \leq m$

$R_m(s)$ is a monic Hurwitz polymonial of degree n

k_m is a constant

As can be seen from the Fig. 7 below, a model is chosen such that it represents the expected or desired behaviour of the plant when the adaptive controller is added to the overall scheme. The deviation of the plant from the desired behaviour determines the required correction of the adaptive parameters. The proposed method requires an operator L(s) such that the transfer function is strictly positive real.

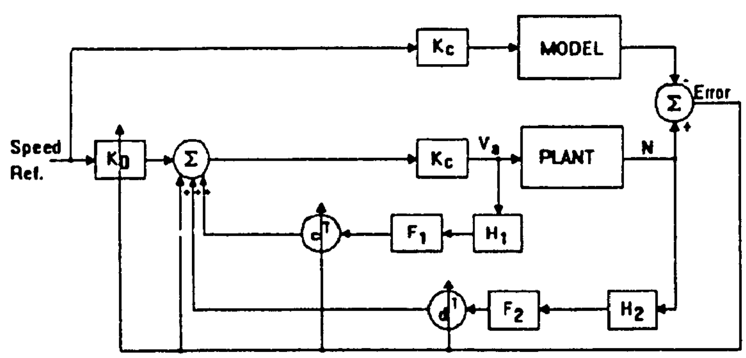

Fig. 7:Basic block diagram of the proposed MRAS direct control system

The complexity of the solution depends to a large extent on the prior information of the plant transfer function. The authors propose this control method and state that the differential equations which are developed assure that all the parameters are bounded and that the output error tends to zero.

As will be shown later, for this application there are a total of 14 differential equations to define the drive control system of which four determine the adaptive control parameters. It is crucial that these adaptive control parameters are bounded and it will be shown in the results that this is truly the case.

The plant consists of a DC motor along with its mechanical load consisting of gears, rolls, couplings, shafts etc. In new installations the characteristics of the plant are known but due to machine usage these characteristics will change. This will require that the drives are capable of responding to both process changes and changes in the system parameters.

The model is therefore required to provide a reference point and a performance index of how the overall system should function. The model will never change since it has been defined in digital form in the system memory and it will always respond in the same manner as originally defined.

The model reference approach could be part of an overall scheme providing a constant gain feedback system in the case the estimated parameters are constant. Therefore, the adaptive loop would become an auto tuner for the control loop. This is accomplished by operating the adaptive regulator until the performance meets the application requirements and it is then disconnected.The system is then run on the fixed parameters found by the regulator.This type of control could then be used in a conventional PID control with three operating modes (manual, automatic and auto tuning mode).

The model reference system used in this paper has been conceived to be used as an adaptive regulator. The model parameters have been calculated based on the well known methods used in conventional feedback control to provide an optimized speed response.

2.5.1 MATHEMATICAL DEVELOPMENT OF THE PROPOSED SYSTEM

The plant state space representation has been defined in the previous section, therefore this section will define the criteria on which the state space model was chosen. The parameters were chosen to provide a transient response based on the conventional method described in [13, pp. 232-233]. Since each type of application has its own response requirements, it may be necessary that different model parameters are used therefore requiring different settings.

The plant has been defined as a second order system, consequentially the model will also be of the same form. In order to specify a transient response for a second order system the damping ratio ξ, peak time t_p, delay time t_d, rise time t_r, maximum overshoot M_p and settling time t_s must all be defined as discussed in [13]. The following parameters were chosen $\xi=0.5$ and $t_r=100$ ms to guarantee a fast and sufficiently damped transient response. This results in a calculated natural frequency w_n of 12.09.

The model state space representation is defined as follows:

$$\begin{bmatrix}\dot{y}_1\\ \dot{y}_2\end{bmatrix}=\begin{bmatrix}a_{m1} & a_{m3}\\ a_{m2} & a_{m4}\end{bmatrix}\begin{bmatrix}y_1\\ y_2\end{bmatrix}+\begin{bmatrix}b_{m1}\\ b_{m2}\end{bmatrix}u_m \tag{19}$$

The characteristic equation is:

$$s^2-(a_{m1}+a_{m4})s+(a_{m1}a_{m4}-a_{m2}a_{m3})=0 \tag{20}$$

where

$$\begin{gathered}w_n^2=a_{m1}a_{m4}-a_{m2}a_{m3}\\ \xi=\frac{a_{m1}+a_{m4}}{2w_n}\end{gathered} \tag{21}$$

Setting $a_{m1}=0, a_{m2}=1$ results in $a_{m4}=-12.09$ and $a_{m3}=-146.2$ which will provide a rise time t_r of 100ms and an overshoot of 16.3% due to the initial setting of ξ to 0.5. This rise time and overshoot is quite acceptable in industry.

If we then combine all the calculated parameters, the state space model is:

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -146.02 & -12.09 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} V_a \tag{22}$$

2.5.2 DEFINITION OF THE ADAPTIVE CONTROL SYSTEM EQUATIONS

The plant which has been defined in this thesis has 2 poles and no zeros and thus has relative degree 2. The equations for the adaptive control system defined in [2] are repeated below for clarity.

$$\begin{aligned} u(t) &= \Theta(t)^T w(t) = \Sigma(\Theta_i(t) + \dot{\Theta}_i(t) L^{-1}) w_i(t) \\ \dot{\Theta}(t) &= -\Gamma e_1(t) L^{-1} w(t) \end{aligned} \tag{23}$$

Defining further each of the various matrices in the above equations:

$$\Gamma = \begin{bmatrix} \gamma_1 & 0 & 0 & 0 \\ 0 & \gamma_2 & 0 & 0 \\ 0 & 0 & \gamma_3 & 0 \\ 0 & 0 & 0 & \gamma_4 \end{bmatrix} \tag{24}$$

$$L(s) = s + \rho \text{ where } \rho > 0 \tag{25}$$

$$e_1(t) = y_p - y_m \tag{26}$$

$$\Theta(t) = \begin{bmatrix} k_0 \\ c_1 \\ d_0 \\ d_1 \end{bmatrix} \tag{27}$$

By combining all the above equations and using the basic block diagram shown in Fig. 7, a detailed block diagram specific to this application can be designed and is shown in Fig. 8. The complete set of equations for the control system are listed below.

The plant state equations are:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -328.46x_1 + -20.09x_2 + 474.9u(t) \end{aligned} \tag{28}$$

The model state equations are:

$$\begin{aligned} \dot{y}_1 &= y_2 \\ \dot{y}_2 &= -146.2y_1 + -12.09y_2 + r(t) \end{aligned} \tag{29}$$

The adaptive control equations are:

$$u(t) = (k_0 r + \dot{k}_0 r_1) + (c_1 v_1 + \dot{c}_1 v_1) + (d_0 x_1 + \dot{d}_0 x_1) + (d_1 v_2 + \dot{d}_1 v_2) \tag{30}$$

$$\begin{aligned} \dot{r}_1 &= r - \rho r_1 \\ \dot{v}_1' &= v_1 - \rho v_1' \\ \dot{x}_1' &= x_1 - \rho x_1' \\ \dot{v}_2' &= v_2 - \rho v_2' \\ \dot{v}_1 &= -v_1 + u \\ \dot{v}_2 &= d_0 x_1 + d_1 v_2 \\ \dot{k}_0 &= -\gamma_1 r_1 (x_1 - y_1) \\ \dot{c}_1 &= -\gamma_2 v_1' (x_1 - y_1) \\ \dot{d}_0 &= -\gamma_3 x_1' (x_1 - y_1) \\ \dot{d}_1 &= -\gamma_4 v_2' (x_1 - y_1) \end{aligned} \tag{31}$$

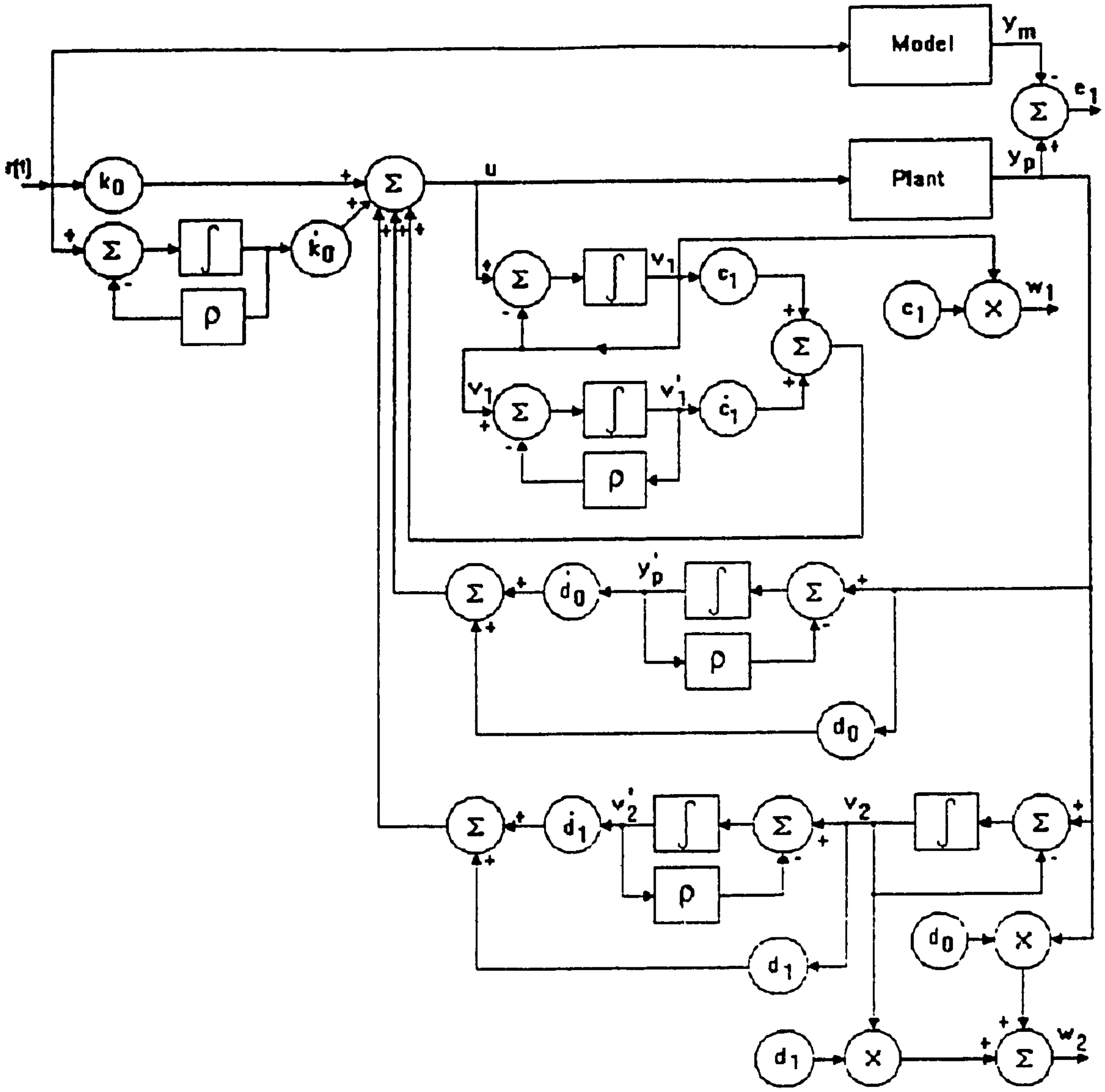

Fig. 8: Detailed block diagram of the proposed MRAS system

2.6 CONVENTIONAL PID SPEED CONTROL SYSTEM

In order to compare the results obtained with the model reference adaptive control system used in this thesis, an equivalent PID speed control system was developed for this application using exactly the same system parameters. The control system parameters were calculated according to the ITAE criterion (Zero-Step Error Systems) [13 p. 301] and the method used in [13 pp. 675-678]. A natural frequency w_n of 12.09 was assumed as on the adaptive control. The state space representation for the PID control is shown below:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -a_3 & -a_2 & -a_1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}+\begin{bmatrix}\beta_1\\ \beta_2\\ \beta_3\end{bmatrix}e_r \tag{32}$$

where the parameters are described below:

$$\begin{aligned}
a_1 &= 20.01+474.9T_d\\
a_2 &= 328.46+474.9K_p\\
a_3 &= 474.9T_i\\
\beta_0 &= 0\\
b_1 &= 474.9T_d\\
b_2 &= 474.9K_p\\
b_3 &= 474.9T_i\\
\beta_1 &= b_1\\
\beta_2 &= b_2-a_1b_1\\
\beta_3 &= b_3-a_1\beta_2-a_2b_1
\end{aligned} \tag{33}$$

A calculation of the same system was made for the PI speed control system but it has not been shown since the PID type of control is commonly used in drives. Due to the fact that a PI system will have a performance which is of lower quality, it can be deduced that the results obtained will also be valid for an equivalent PI speed control system.

3. RESULTS

In the following sections, the results for the PID conventional control and the adaptive control systems will be presented.

In order to insure that both methods provide results which can be compared, the following criteria were used for both control methods:

- The time duration of the simulation was 14 seconds. This is quite reasonable since both systems have had the opportunity to stabilize at this point.
- A step input of 10% was applied to both systems at time t=8 sec.
- The plant parameters were changed for both systems immediately before the step input was applied.

3.1 RESULTS FOR THE PID CONTROL

The results for the PID control have been generated using MATLAB with its ODE45 function for the solution of the differential equations. The PID parameters which were used in the simulations were based on the ITAE standards; they are: T_i=3.72, K_p=-0.0299, and T_d=0.0024. With these parameters the speed response is overdamped. The simulation results are shown in Appendix A and include speed response, motor acceleration and speed error as follows:

- The first simulation is one with no system parameter variations. These results are shown in Figures 1 through 3.
- The second simulation was done with the armature resistance R_a changing by 1.5 times the nominal value. These results are shown in Figures 4 through 6.
- The third simulation was done with the friction constant B changing by 1.5 times the nominal value. These results are shown in Figures 7 through 9.
- The fourth simulation was done with the motor constant parameter $K_a\Phi$ changing by 1.5 times the nominal value. These results are shown in Figures 10 through 12.
- The fifth simulation was done with the parameters R_a, B, $K_a\Phi$ all changing by 1.5 times the nominal value.These results are shown in Figures 13 through 15.

The simulations demonstrate that as long as the system parameters don't change, the quality of the speed response is maintained. A change in one of the system parameters will affect how the overall system operates affecting the maintenance as well as the quality of the end product. In order to return the system to its optimal operating efficiency, retuning of the drive is required.

3.2 RESULTS FOR THE ADAPTIVE CONTROL

The simulation results, which can be found in Appendix B, were obtained with the use of a combination of the VAX IMSL mathematical program library to calculate the various parameters described by the 14 differential equations and MATLAB to interpret and plot the data.

In this adaptive control technique, there are basically five control parameters with which it is possible to modify the response of the control system; these control parameters are ρ, γ_1, γ_2, γ_3 and γ_4. The simulation results are shown in Appendix B and include motor speed response, motor acceleration, model speed, model acceleration, speed error, plant speed reference u(t), adaptive parameter k_0, adaptive parameter c_1, adaptive parameter d_0 and adaptive parameter d_1 as follows:

- The first simulation is one with no system parameter variations. These results are shown in Figures 1 through 10.
- The second simulation was done with the armature resistance R_a changing by 1.5 times the nominal value. These results are shown in Figures 11 through 20.
- The third simulation was done with the friction constant B changing by 1.5 times the nominal value. These results are shown in Figures 21 through 30.

- The fourth simulation was done with the motor constant parameter $K_a\Phi$ changing by 1.5 times the nominal value. These results are shown in Figures 31 through 40.
- The fifth simulation was done with the parameters R_a, B, $K_a\Phi$ all changing by 1.5 times the nominal value. These results are shown in Figures 41 through 50.

From the curves found in Appendix B, it can be seen that the adaptive control is in a learning mode in the first few seconds. By varying the gains, the learning and the speed response are affected; therefore, proper choice of the parameters ρ, γ_1, γ_2, γ_3 and γ_4 is very important to the performance of the system. As a result of all the simulations done during the research phase of this thesis, the control parameters were chosen as ρ=10, γ_1=250, γ_2=120, γ_3=120 and γ_4=160.

The simulation results included in Appendix B, show that the performance of the control system does not change with the plant parameter variations which can occur during the life of the equipment. Therefore, the adaptive control can provide the same performance throughout the normal operating life of the system; this would reduce the maintenance costs and maintain the operating efficiency of the system, providing a more stable operation which will be less sensitive to the changes in the plant equipment.

4. CONCLUSION

This thesis has demonstrated that the proposed model reference adaptive control method together with a DC motor can provide a technically advanced solution. The results show that the performance of the drive system retains its features even though the plant parameters have changed. These plant changes are very possible due to aging of the equipment or different operating modes of the plant. For example, a 50% increase in resistance may result in an operating temperature rise of the motor windings which may be well below its rated values depending on the ambient temperature and the insulation class.

This thesis proposes an adaptive control method which has not been considered for drive applications since the present main research areas are in the VSS type of adaptive control. It has been shown that the proposed method will provide the required performance as compared to the PID control method. It can be noticed that the speed response for the PID control is altered with a change of parameters. This would be detrimental in applications such as steel, where the impact speed drop is of crucial importance for ideal production to take place. Impact speed drop has been a main concern for drive performance especially in the steel industry. The adaptive control response shows that there is no change even though the plant parameters change.

The choice of the control parameters ρ, γ_1, γ_2, γ_3 and γ_4 will determine the operation of the plant (i.e. speed response, stability etc.) which of course are dependent on the model design. Once the control parameters are established, the adaptive control will respond in the same way due to the use of digital technology and will compensate for the plant changes. Therefore, the challenge would be to find the right parameters for the model which will provide the desired performance.

The adaptive control system can also function as an auto tuning system. This could simplify the commissioning and servicing of the equipment (for example when the motor is changed due to malfunction). The control system could be switched into the auto tuning mode with an initial set of parameters and then letting the adaptive control function find the final values of the control parameters k_0, c_1, d_0, d_1. This would reduce commissioning time and downtime of the machine for maintenance, as well as simplifying the work of the service or maintenance people.

Further research would be required to establish whether the second order model is adequate to take into account weak mechanical systems which could make the order of the plant greater than a second order system. If this would be the case the simplicity of such a control system could be of tremendous value.

APPENDIX A

PID RESULTS

The following figures show the speed response of the PID control system. The responses have been simulated for both stable and varying conditions for the system parameters. The system parameters which were changed are the motor resistance R_a, the friction constant B or the motor constant $K_a\Phi$. One set of simulations is shown with all the above parameters changed together, simulating a worse case condition of the system operation.

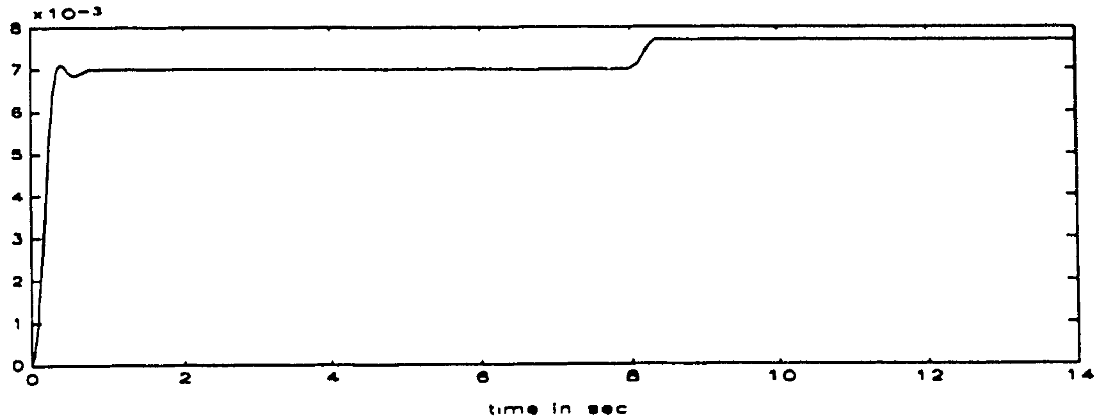

Fig. 1: Speed response with no change in parameters

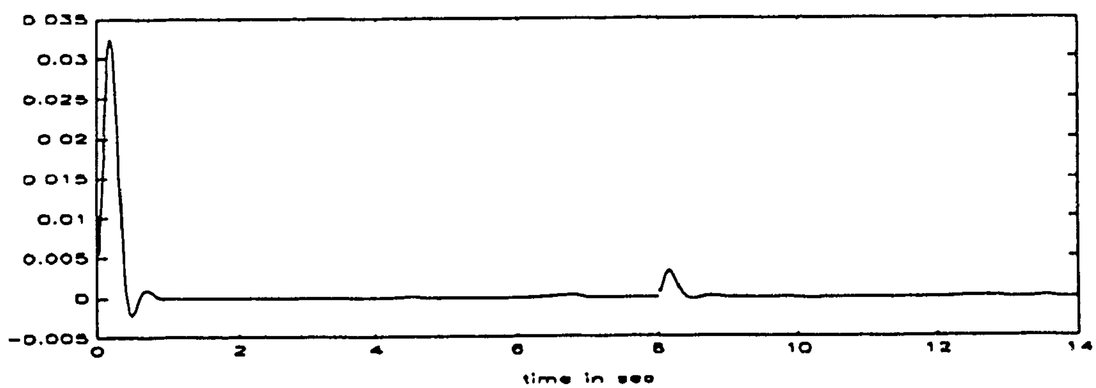

Fig. 2: Acceleration with no change in parameters

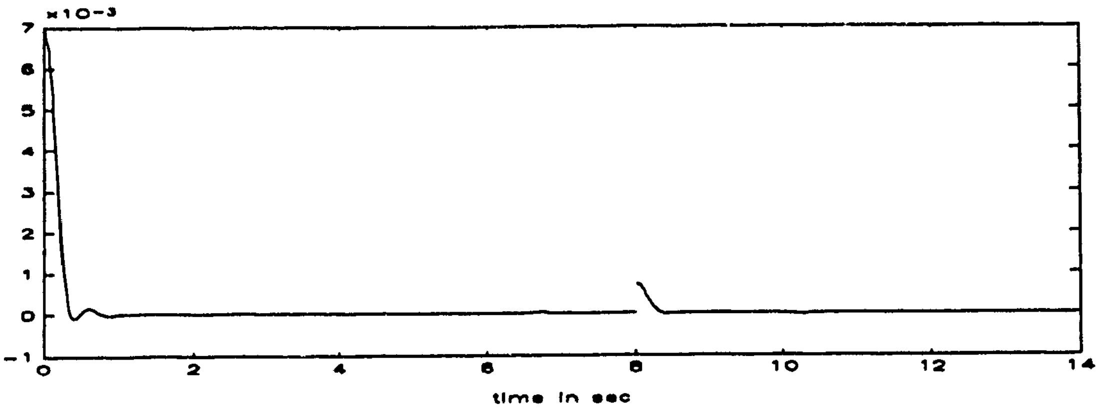

Fig. 3: Speed error with no change in parameters

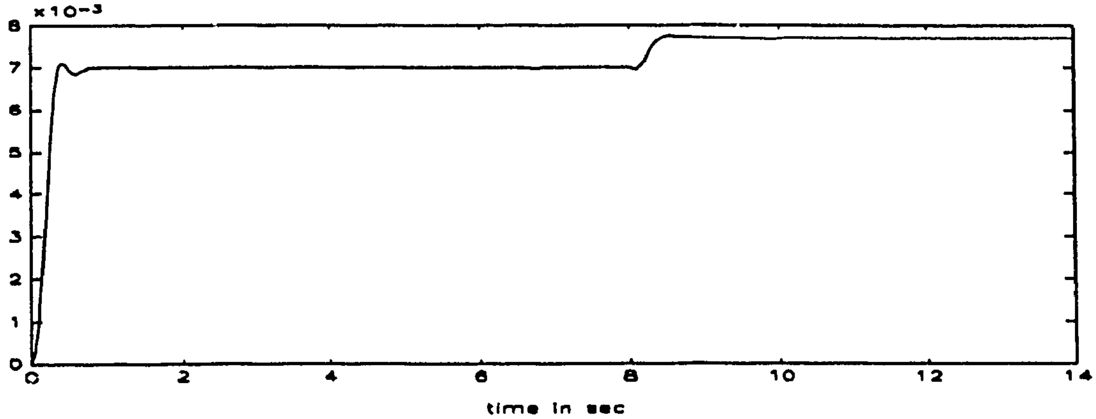

Fig. 4: **Speed response with resistance R_a changed by 1.5 times**

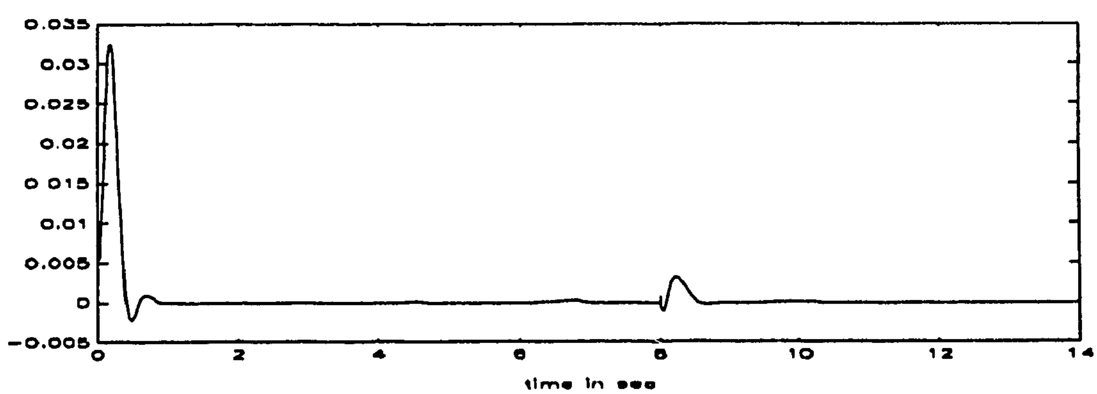

Fig. 5: **Acceleration with resistance R_a changed by 1.5 times**

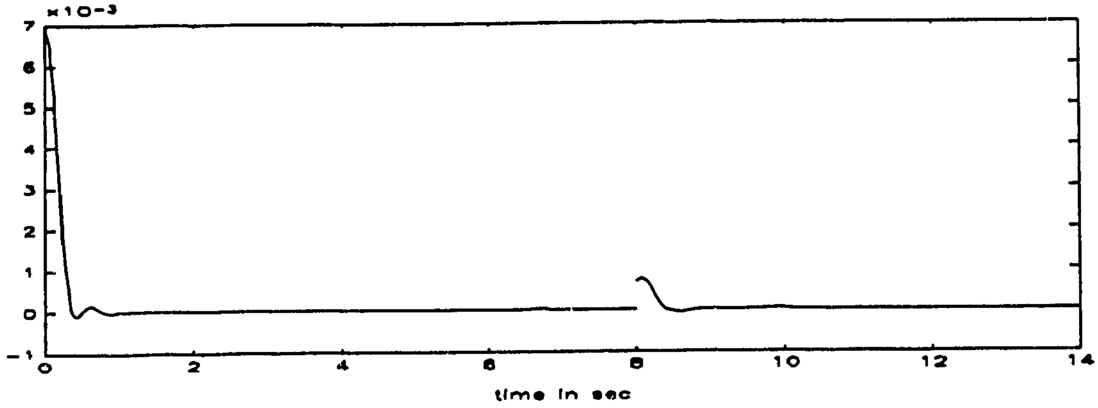

Fig. 6: Speed error with resistance R_a changed by 1.5 times

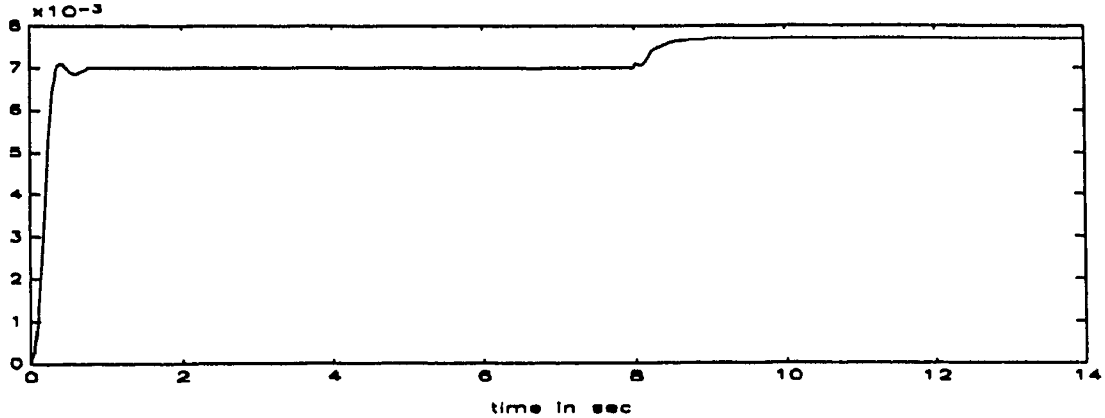

Fig. 7: Speed response with $K_a\Phi$ changed by 1.5 times

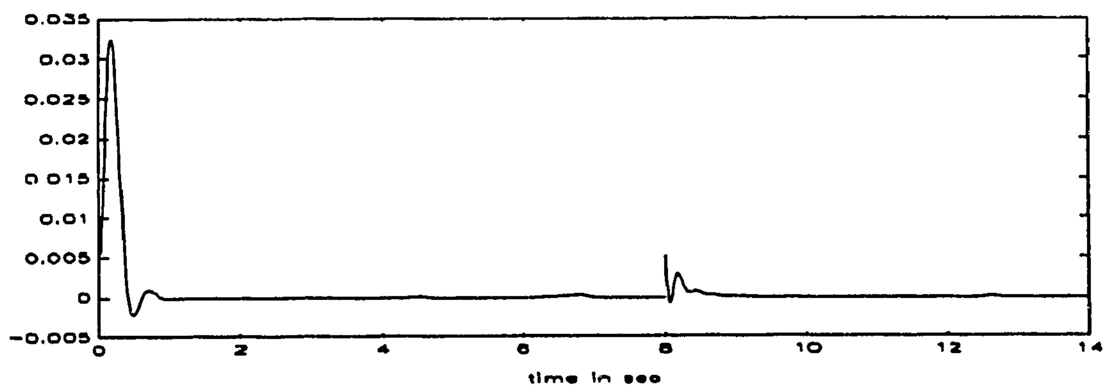

Fig. 8: Acceleration with $K_a\Phi$ changed by 1.5 times

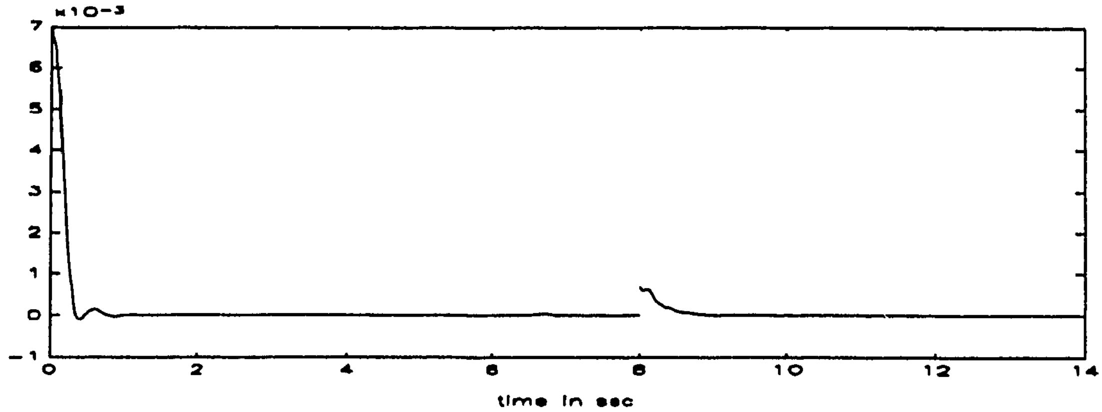

Fig. 9: Speed error with $K_a\Phi$ changed by 1.5 times

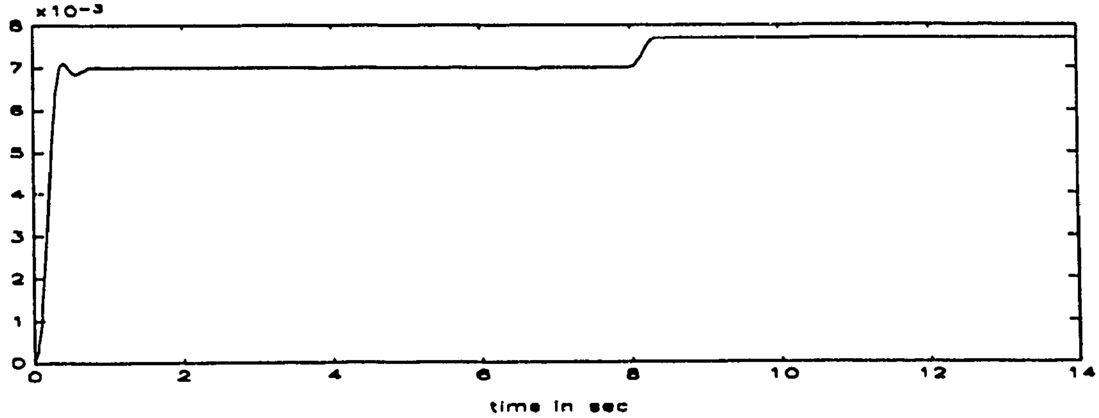

Fig. 10: Speed response with B friction constant B changed by 1.5 times

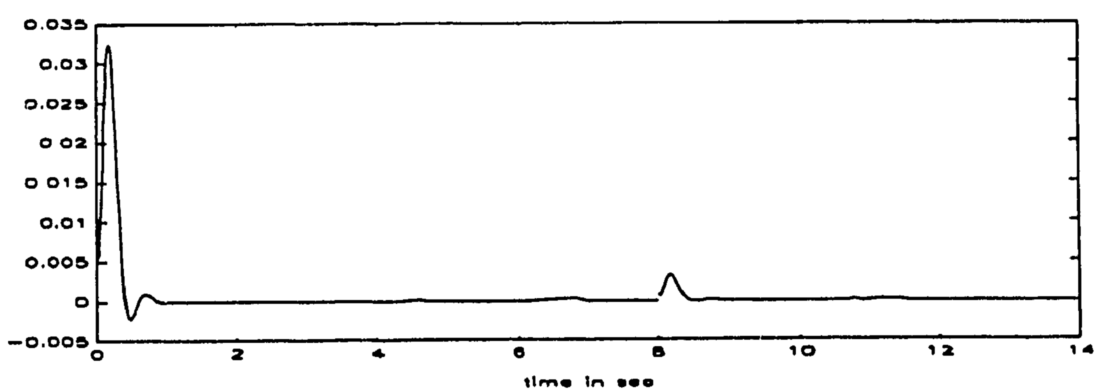

Fig. 11: Acceleration with friction constant changed by 1.5 times

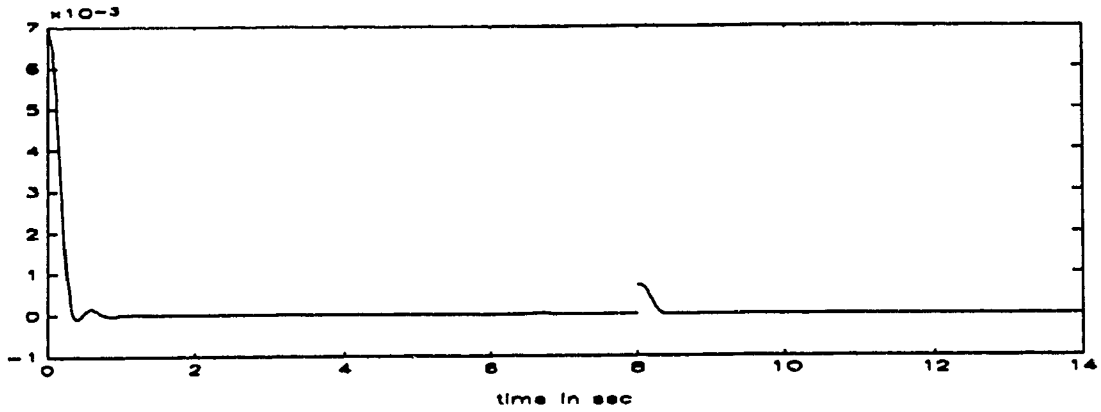

Fig. 12: Speed error with friction constant changed by 1.5 times

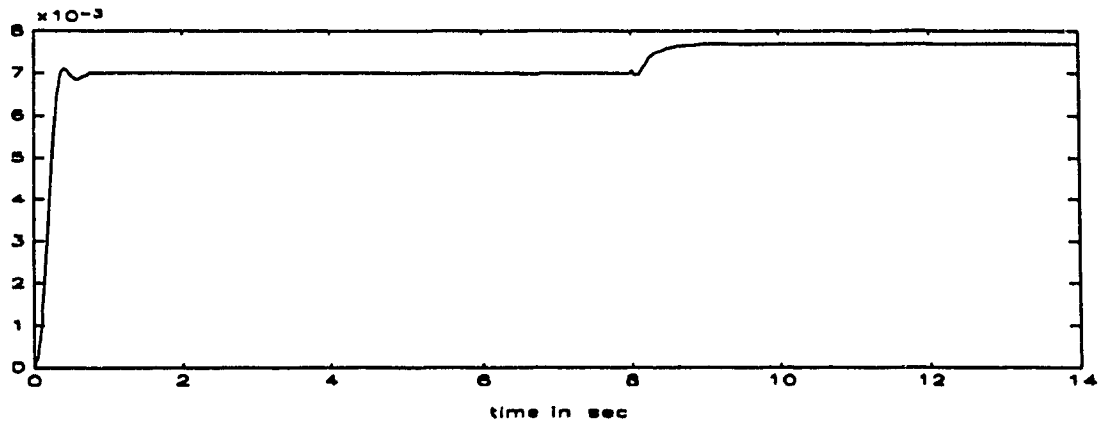

Fig. 13: Speed response with $K_a\Phi$, R_a and B change by 1.5 times

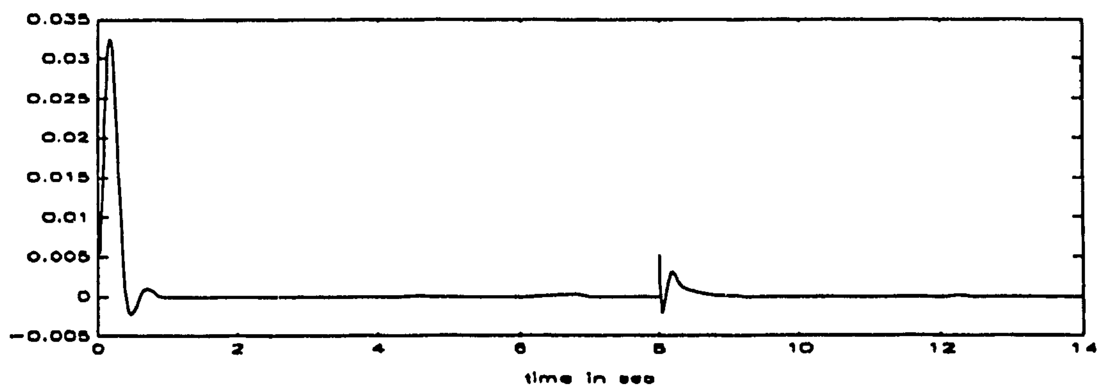

Fig. 14: Acceleration with $K_a\Phi$, R_a and B changed by 1.5 times

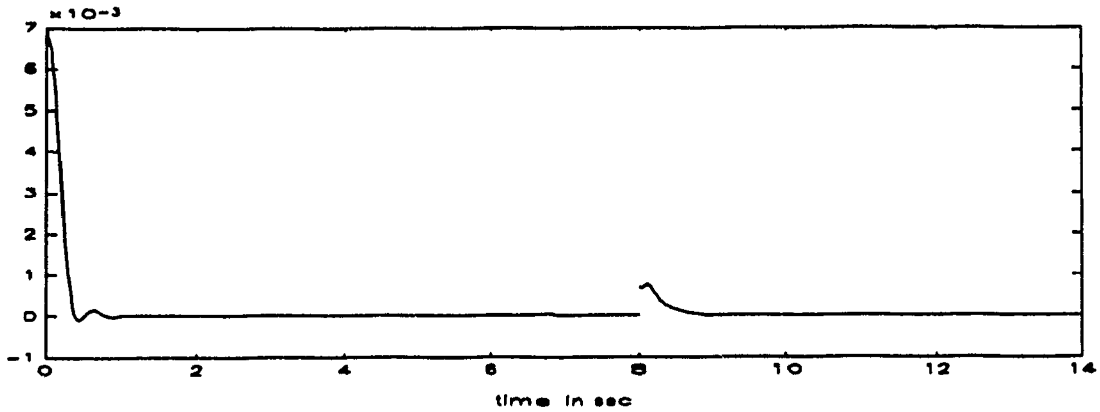

Fig. 15: Speed error with $K_a\Phi$, R_a and B changed by 1.5 times

APPENDIX B

ADAPTIVE CONTROL RESULTS

The following figures are a collection of results for the adaptive control. The figures show results for the performance of the adaptive control system with the same parameter perturbations which were introduced in the PID control system. The figures show results for the system with no parameter perturbations and the with parameter changes of the resistance, friction constant or the motor constant. Finally, one simulation was done with all the system parameter variations happening at the same time to simulate a worst case condition.

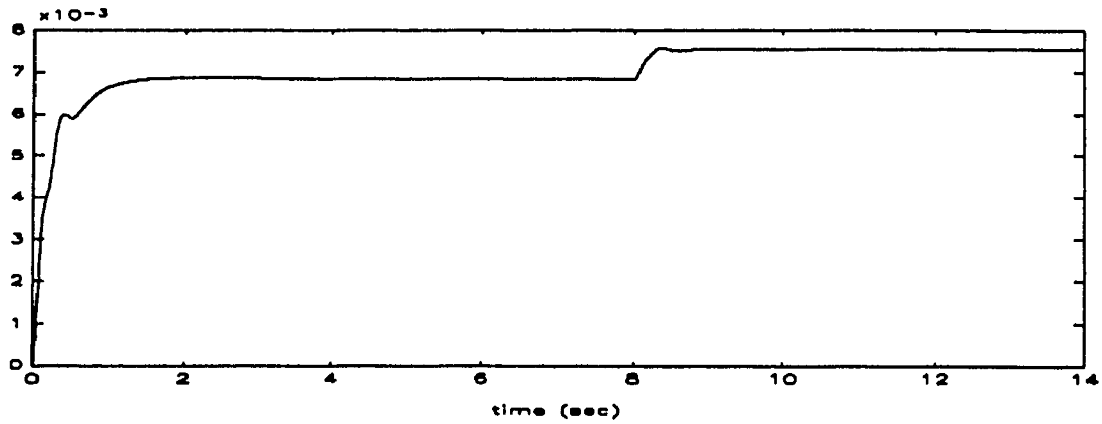

Fig. 1: Motor speed with no change of parameters

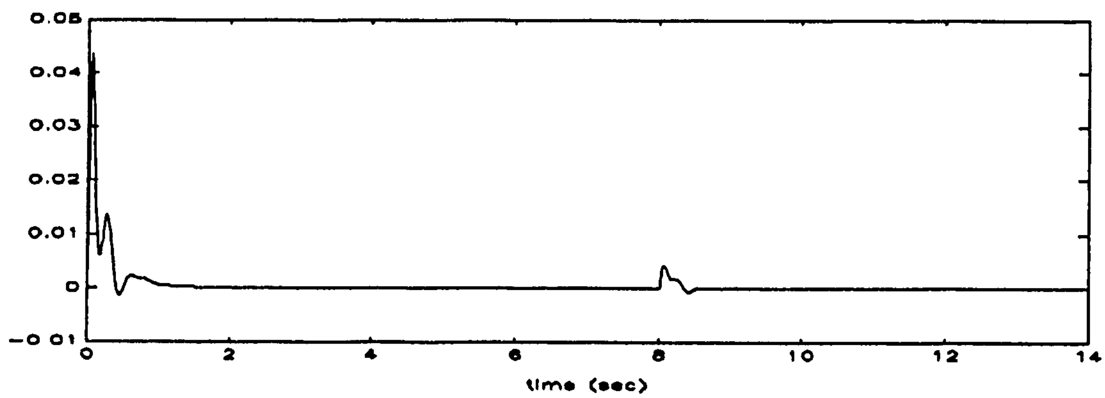

Fig. 2: Motor acceleration with no change of parameters

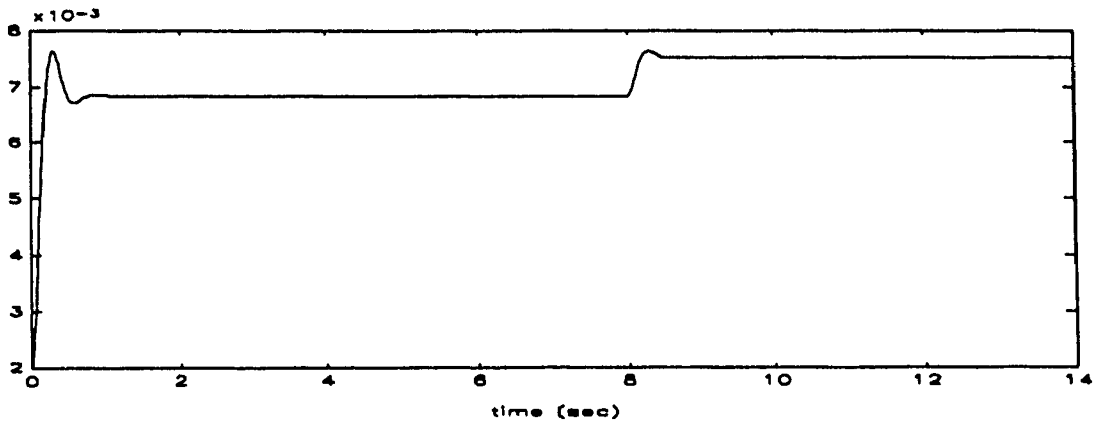

Fig. 3: Model speed response with no change of parameters

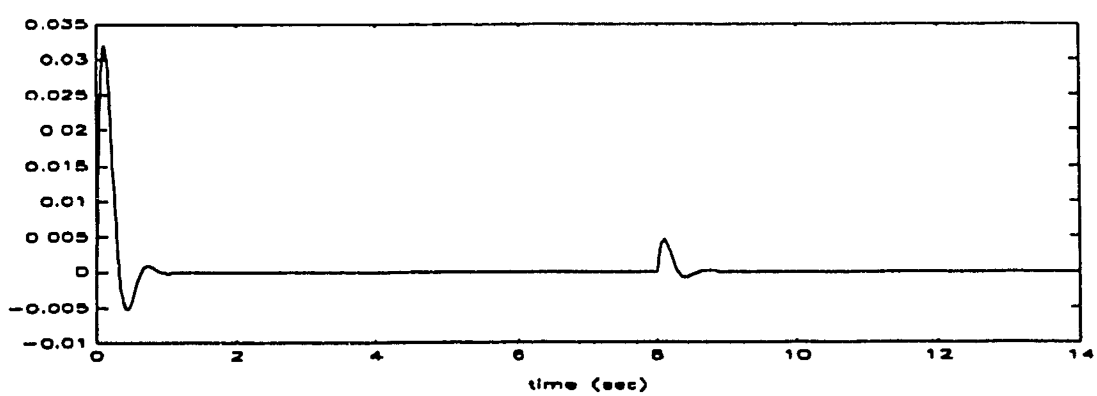

Fig. 4: Model acceleration with no change of parameters

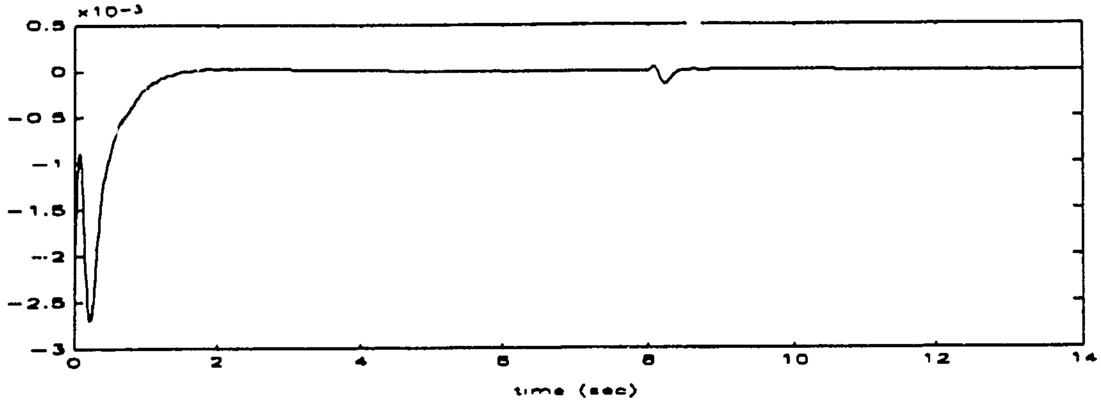

Fig.5: Speed error with no change of parameters

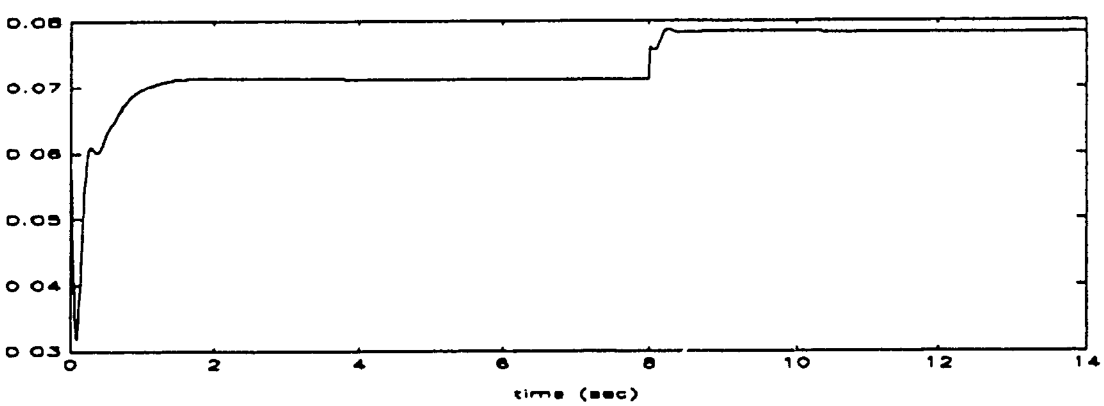

Fig. 6: Plant reference u_1 with no change of parameters

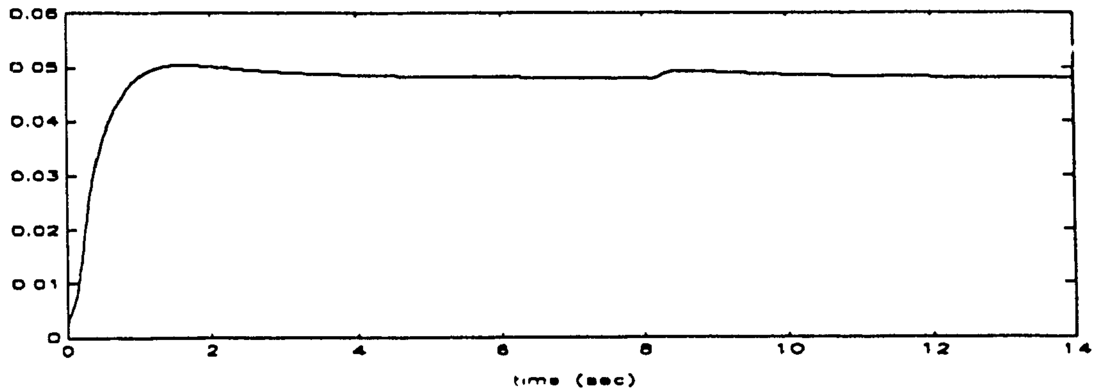

Fig. 7: Adaptive control parameter k_0 with no change of parameters

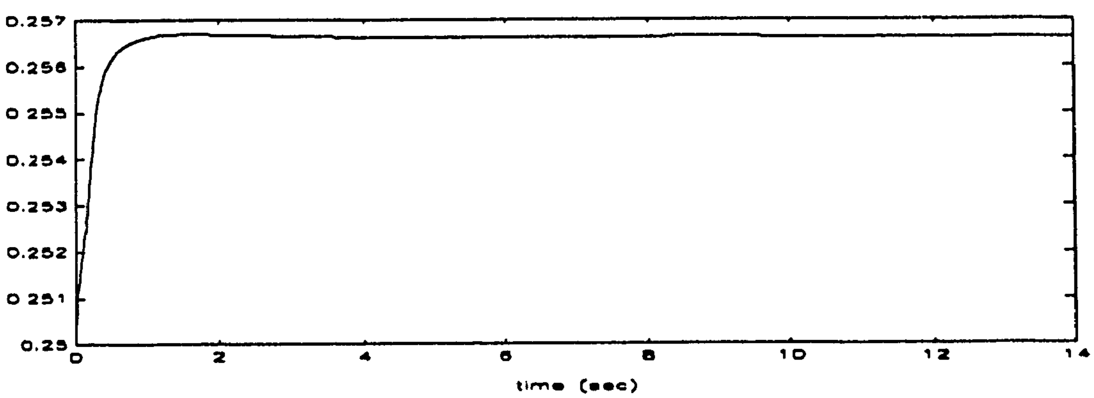

Fig. 8: Adaptive control parameter c_1 with no change of parameters

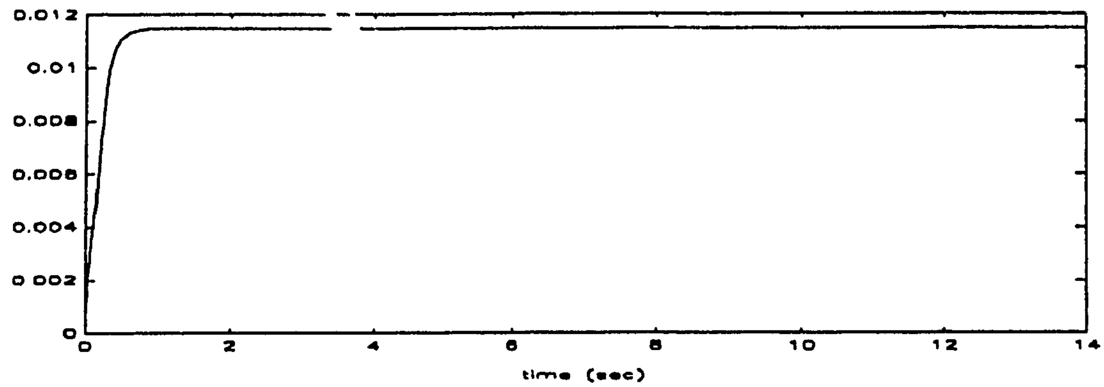

Fig. 9: Adaptive control parameter d_0 with no change of parameters

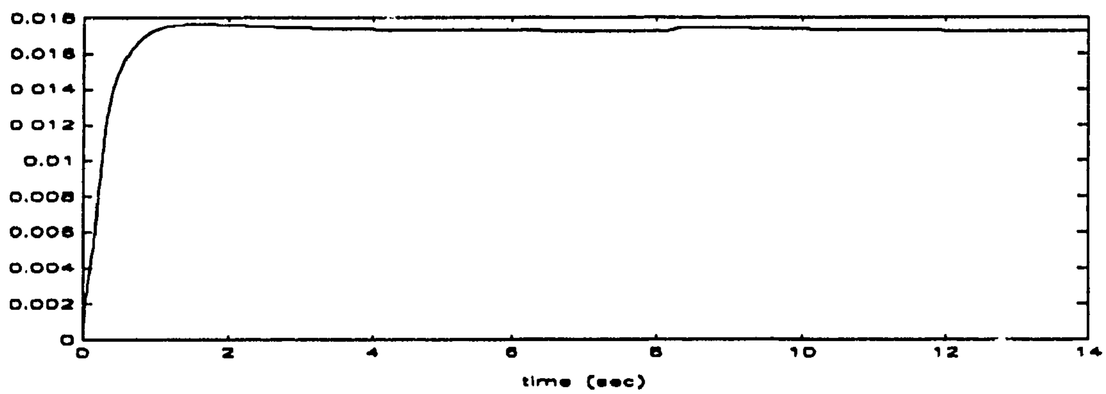

Fig. 10: Adaptive control parameter d_1 with no change of parameters

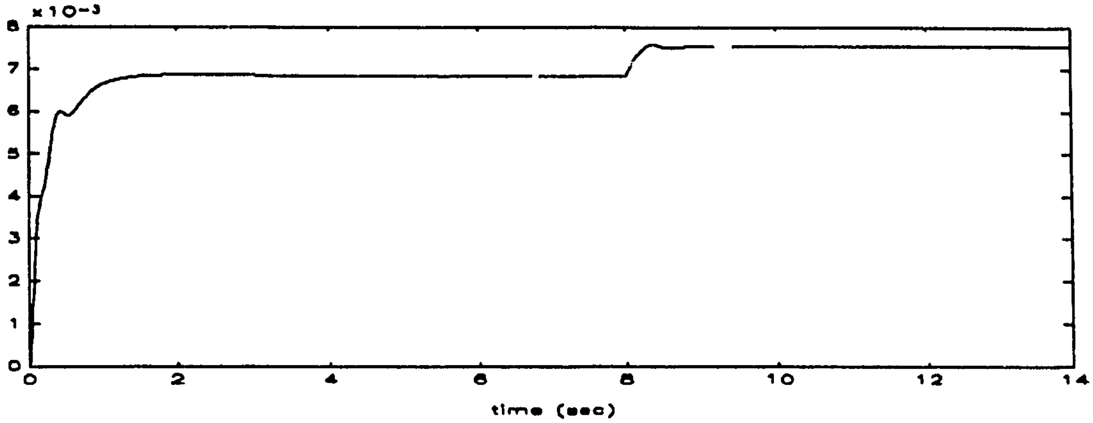

Fig. 11: Motor speed response with R_a changed by 1.5 times

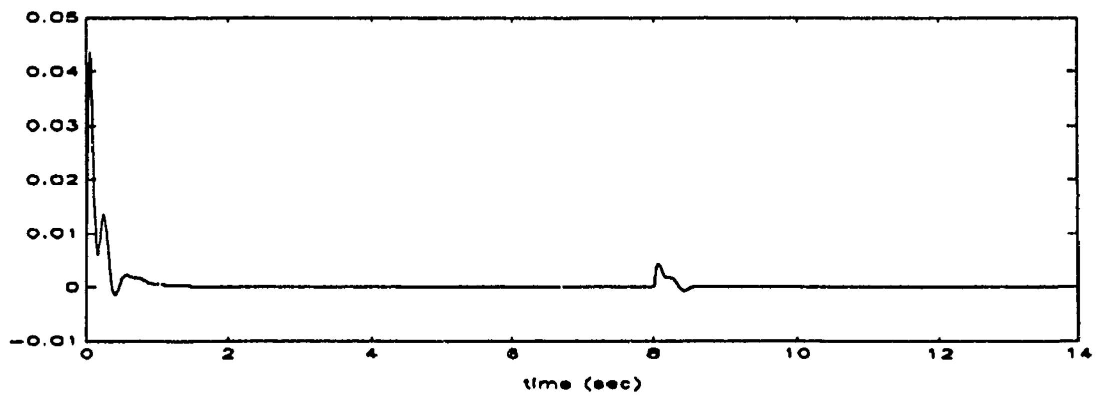

Fig. 12: Motor acceleration with R_a changed by 1.5 times

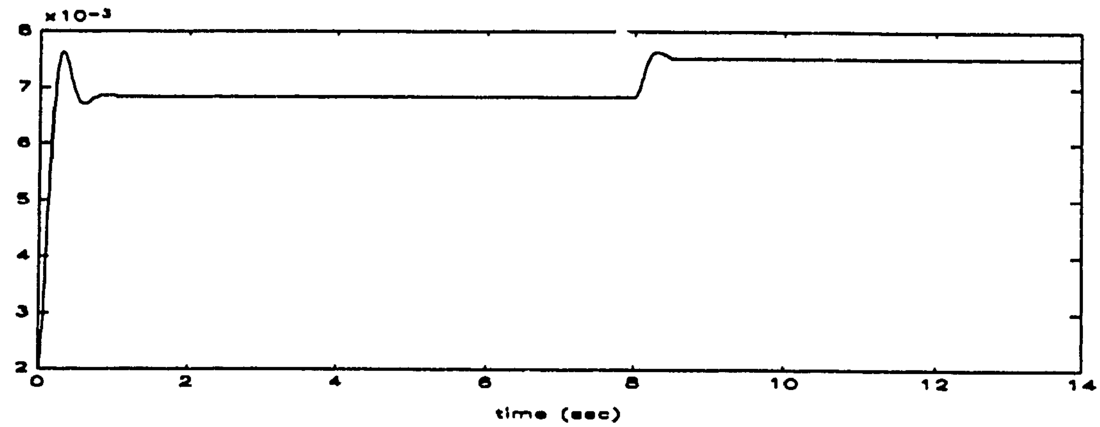

Fig. 13: Model response with R_a changed by 1.5 times

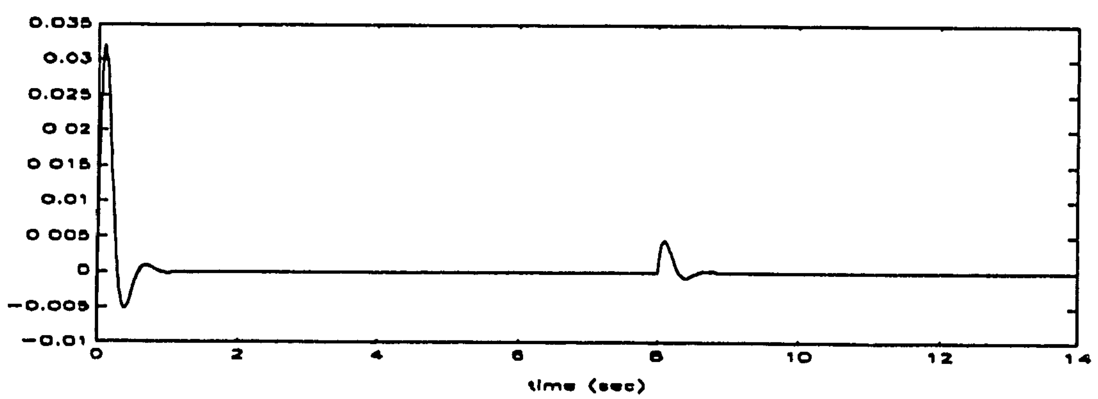

Fig. 14: Model acceleration with R_a changed by 1.5 times

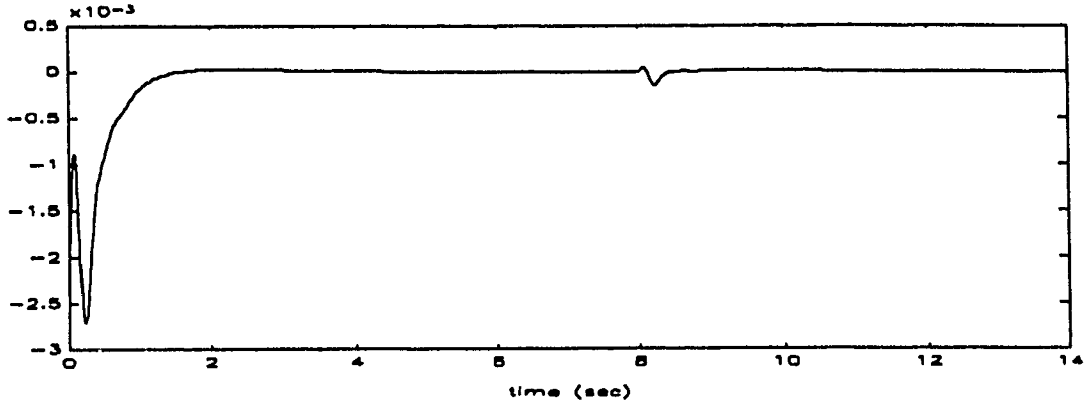

Fig. 15: Speed error with R_a changed by 1.5 times

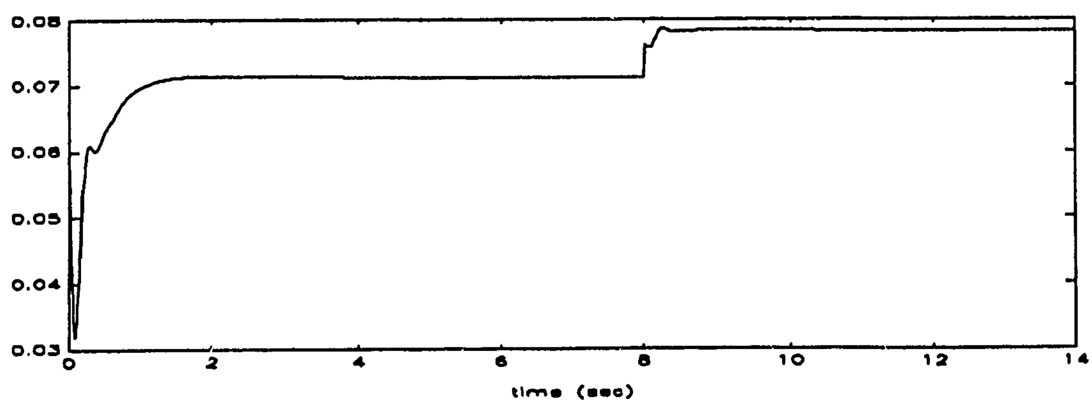

Fig. 16: Plant reference u_1 with R_a changed by 1.5 times

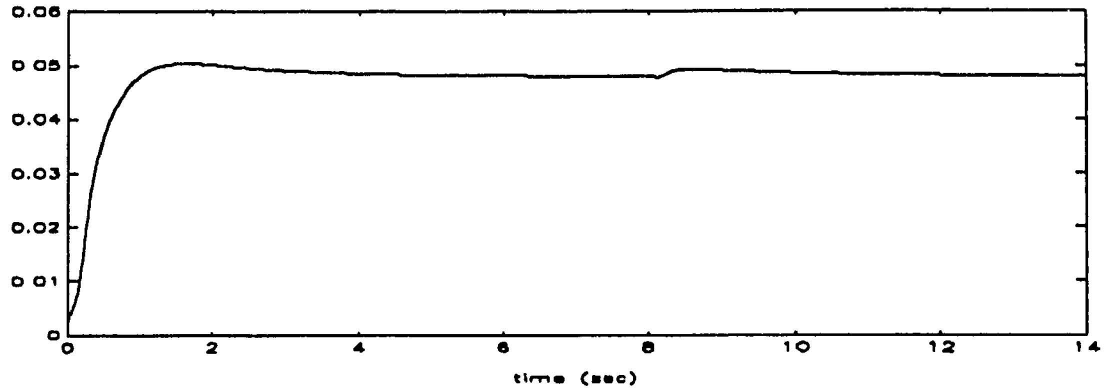

Fig. 17: Adaptive control parameter k_0 with R_a chnaged by 1.5 times

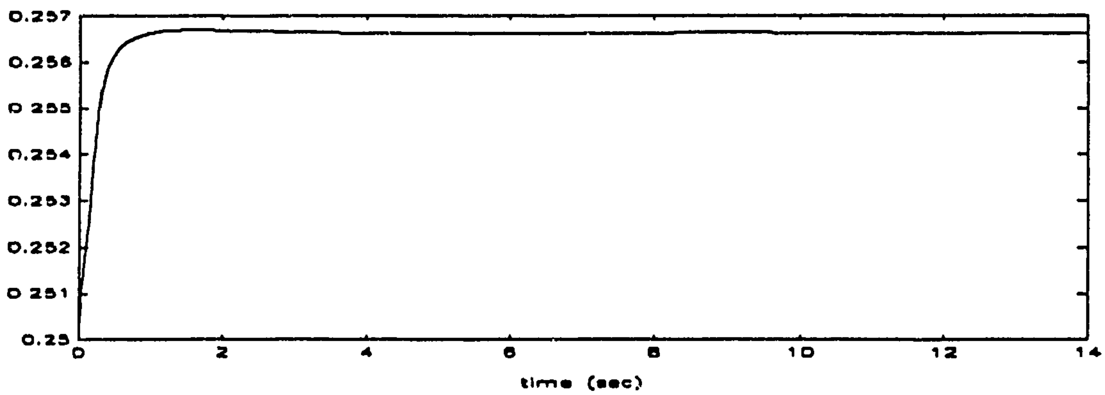

Fig. 18: Adaptive control parameter c_1 with R_a changed by 1.5 times

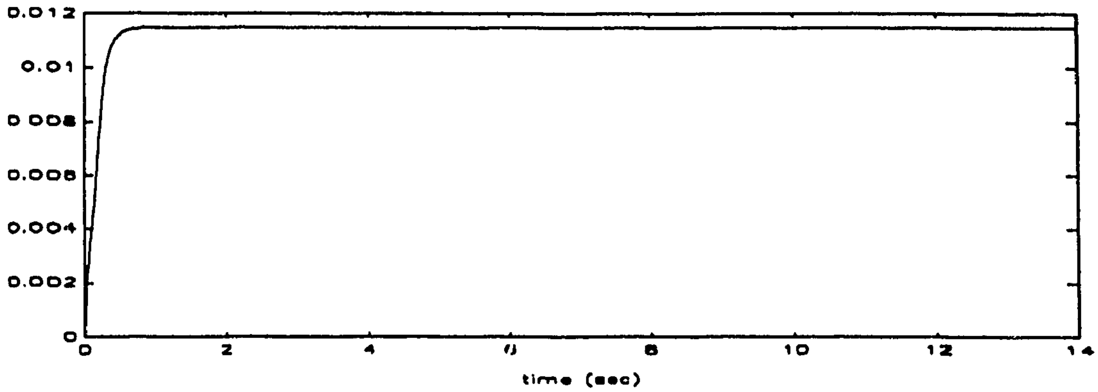

Fig. 19: Adaptive control parameter d_0 with R_a changed by 1.5 times

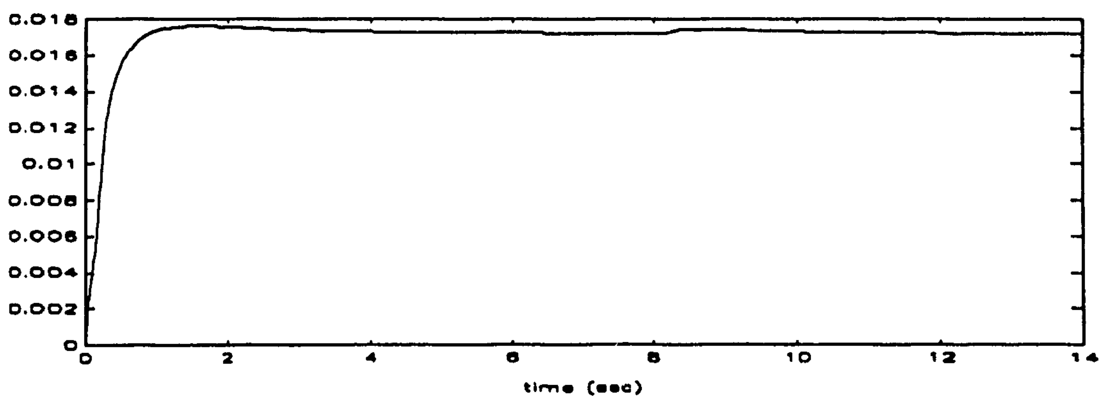

Fig. 20: Adaptive control parameter d_1 with R_a changed by 1.5 times

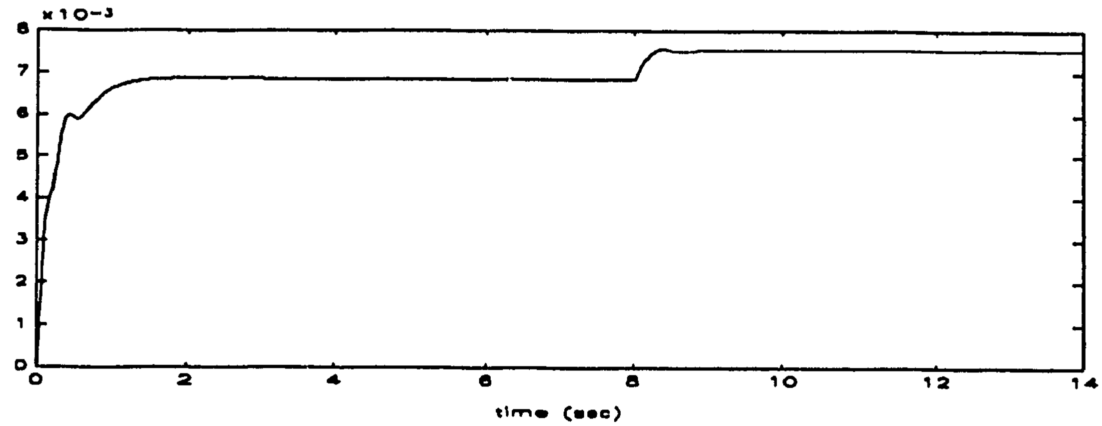

Fig. 21: Speed response with parameter $K_a\Phi$ changed by 1.5 times

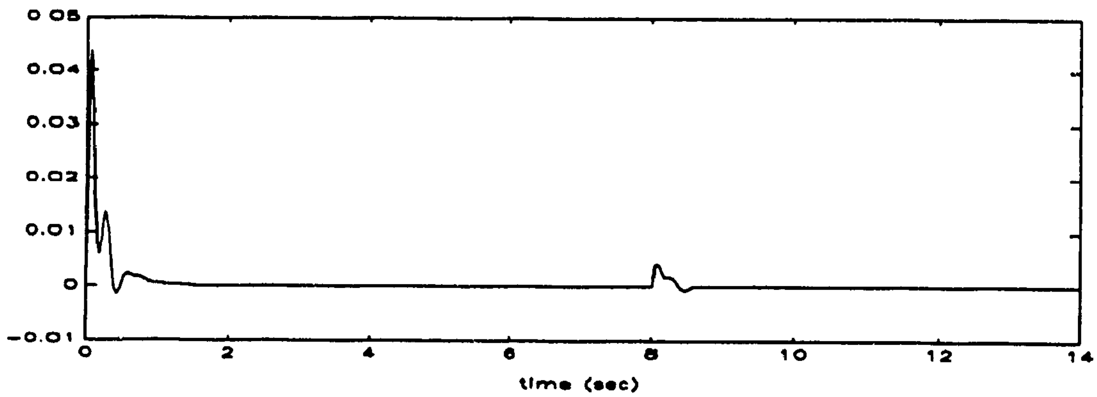

Fig. 22: Motor acceleration with parameter $K_a\Phi$ changed by 1.5 times

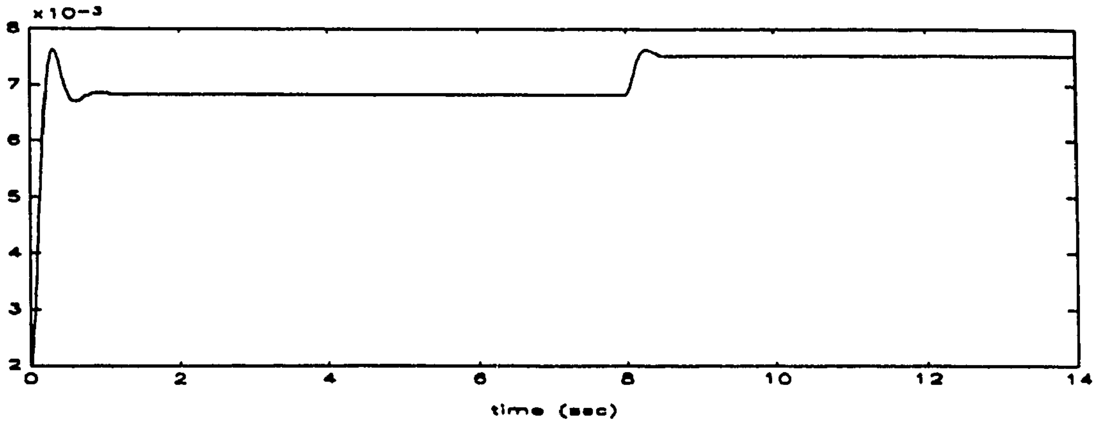

Fig. 23: **Model speed with parameter $K_a\Phi$ changed by 1.5 times**

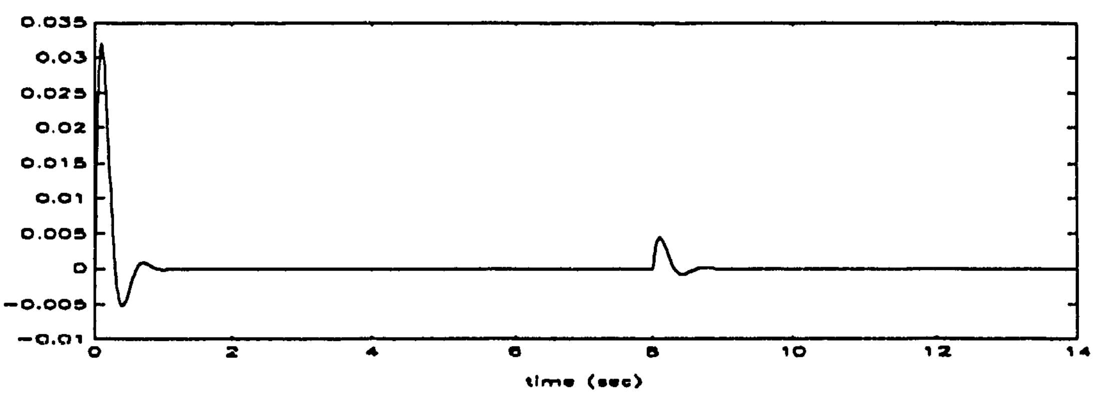

Fig. 24: **Model acceleration with parameter $K_a\Phi$ changed by 1.5 times**

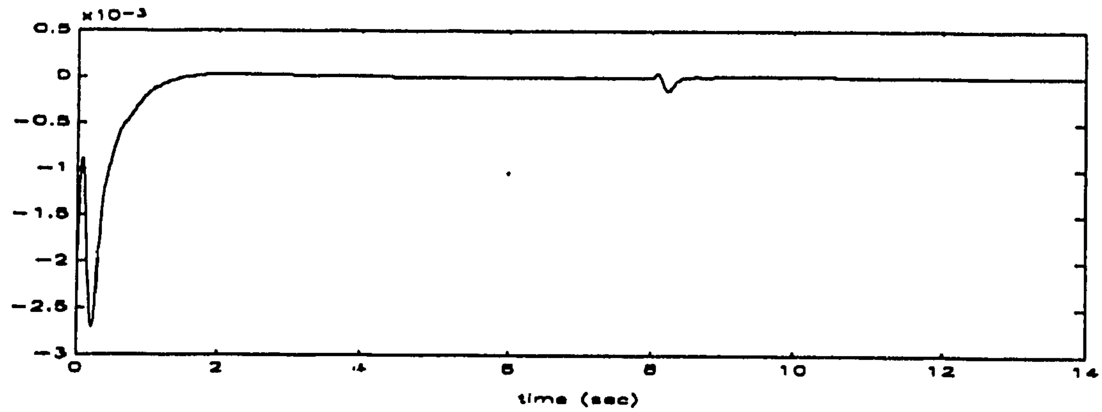

Fig. 25: Speed error with parameter $K_a\Phi$ changed by 1.5 times

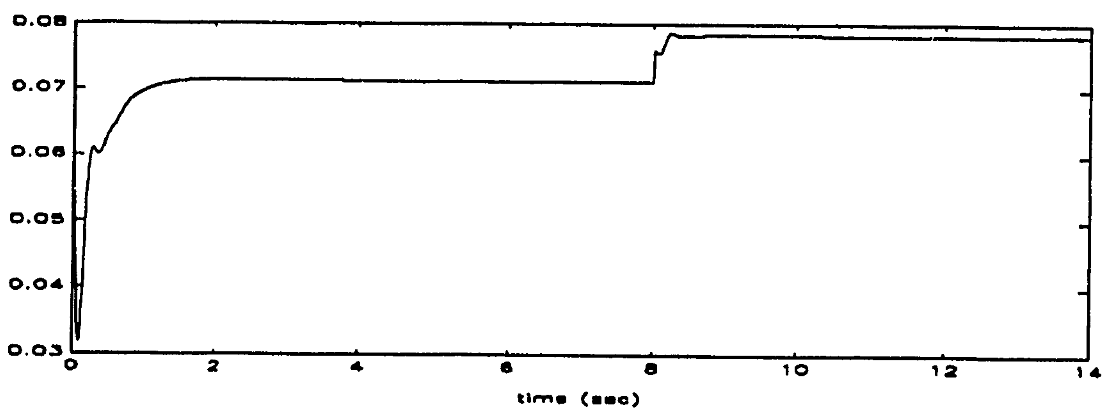

Fig. 26: Plant reference u_1 with parameter $K_a\Phi$ changed by 1.5 times

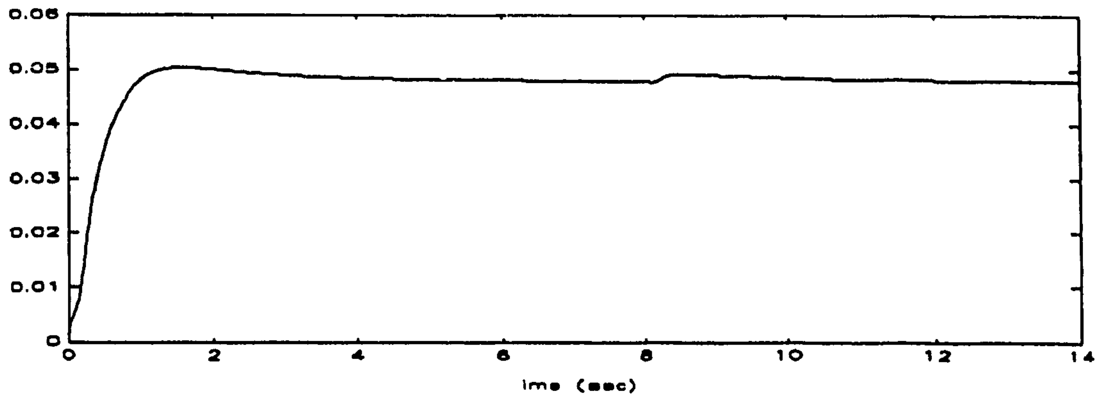

Fig. 27: Adaptive control parameter k_0 with $K_a\Phi$ changed by 1.5 times

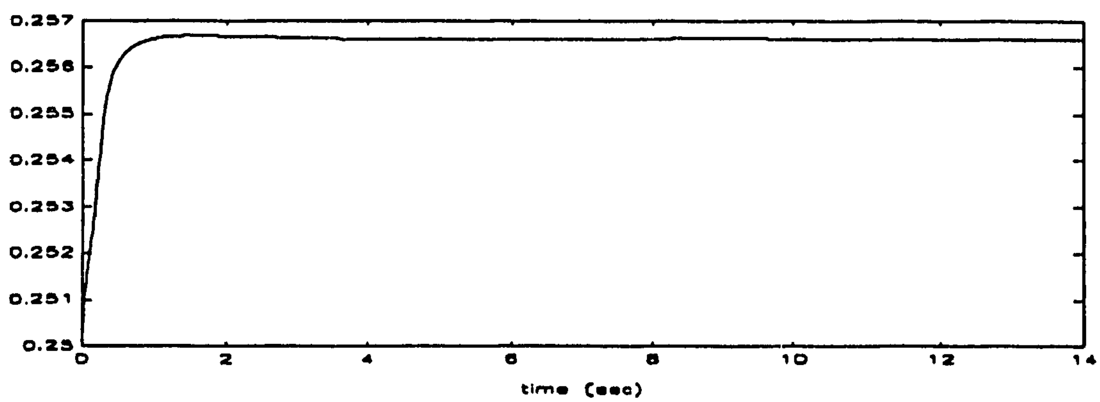

Fig. 28: Adaptive control parameter c_1 with $K_a\Phi$ changed by 1.5 times

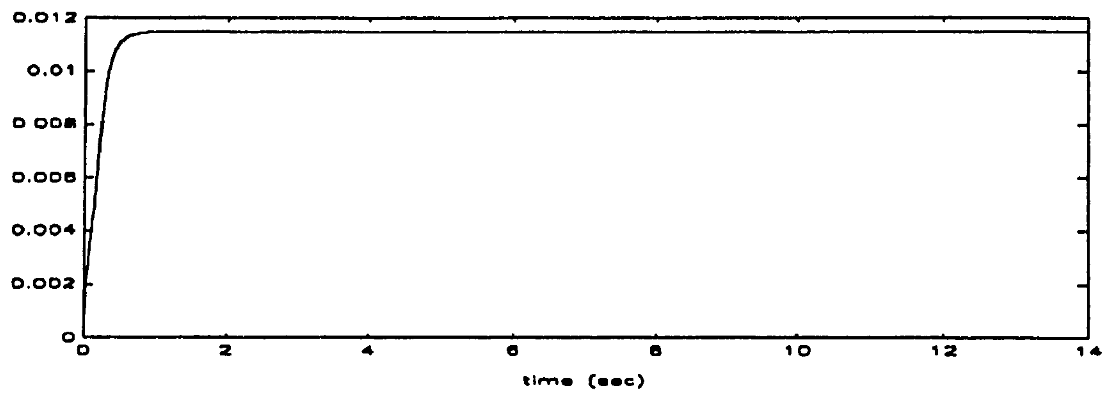

Fig. 29: Adaptive control parameter d_0 with $K_a\Phi$ changed by 1.5 times

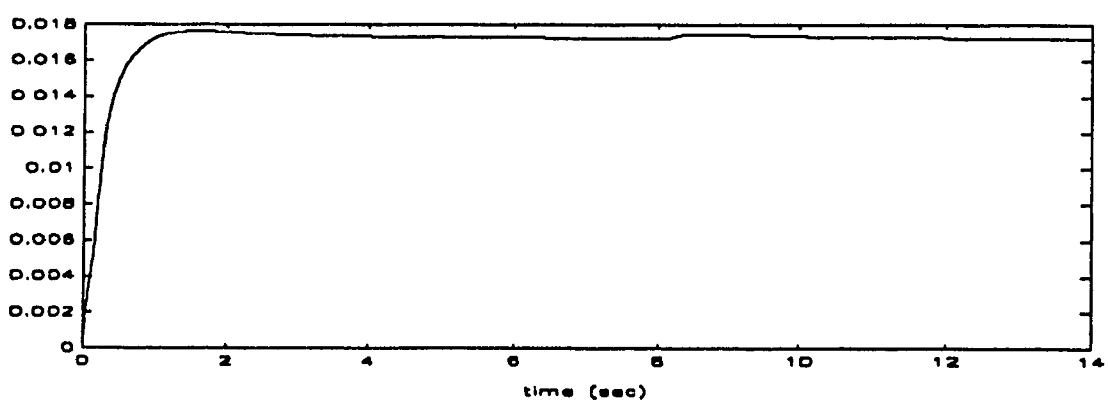

Fig. 30: Adaptive control parameter d_1 with $K_a\Phi$ changed by 1.5 times

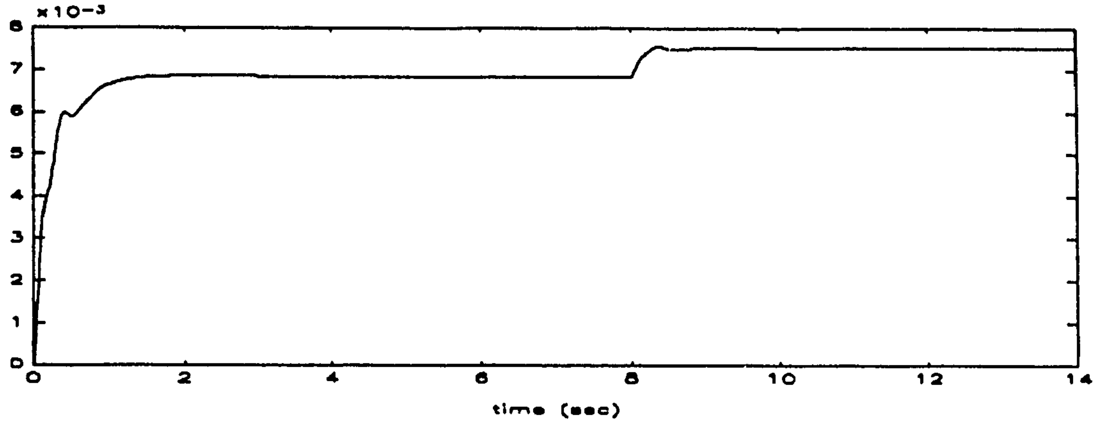

Fig. 31: Speed response with friction parameter B changed by 1.5 times

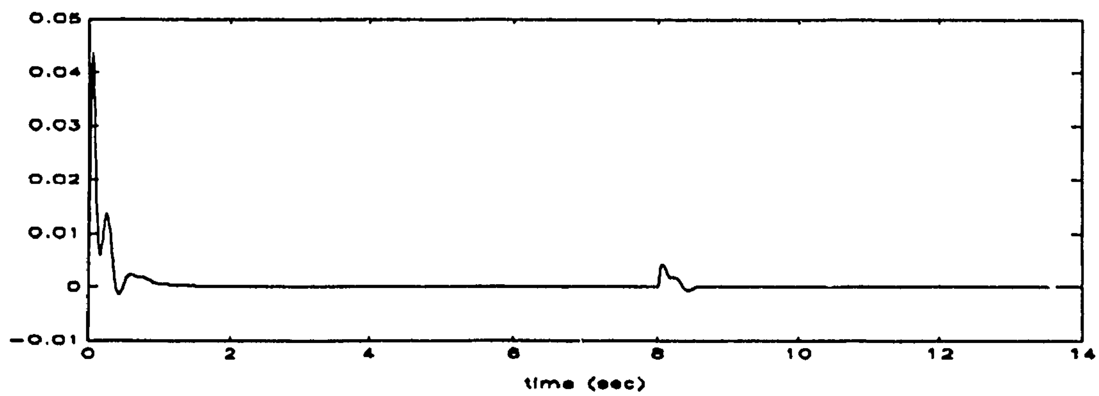

Fig. 32: Acceleration with friction parameter B changed by 1.5 times

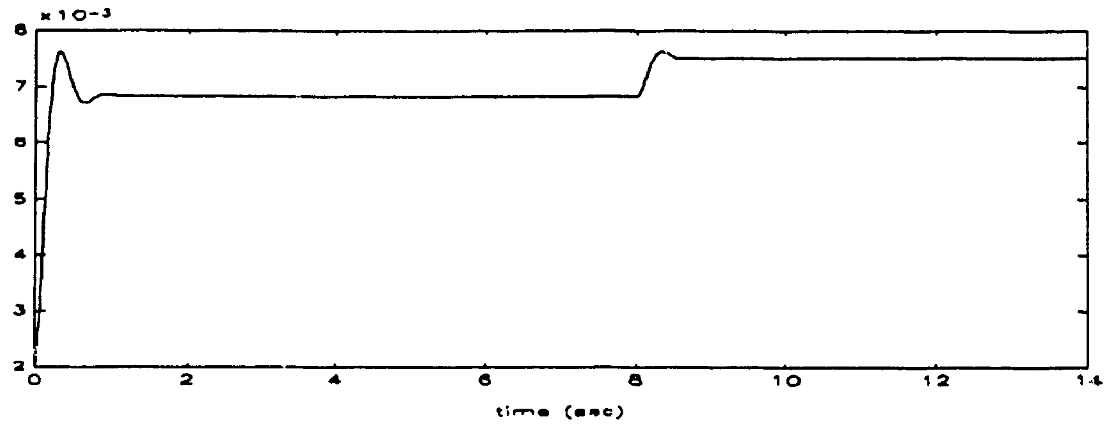

Fig. 33: Model speed response with friction parameter B changed by 1.5 times

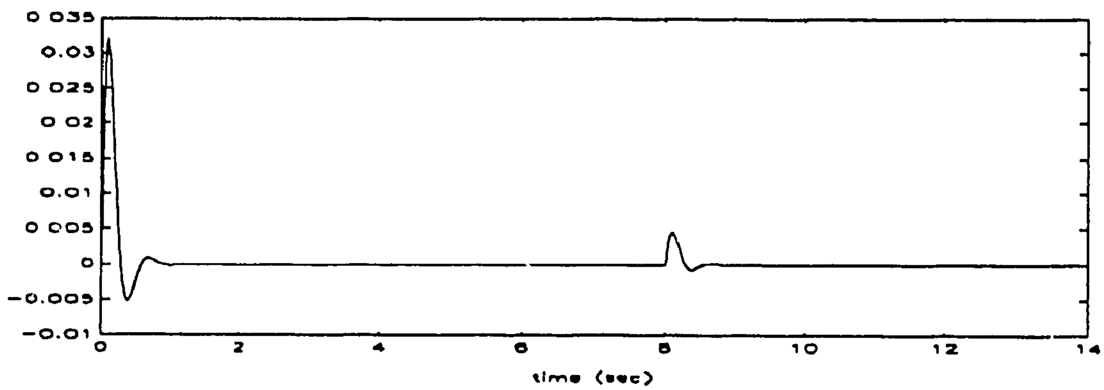

Fig. 34: Model acceleration with friction parameter B changed by 1.5 times

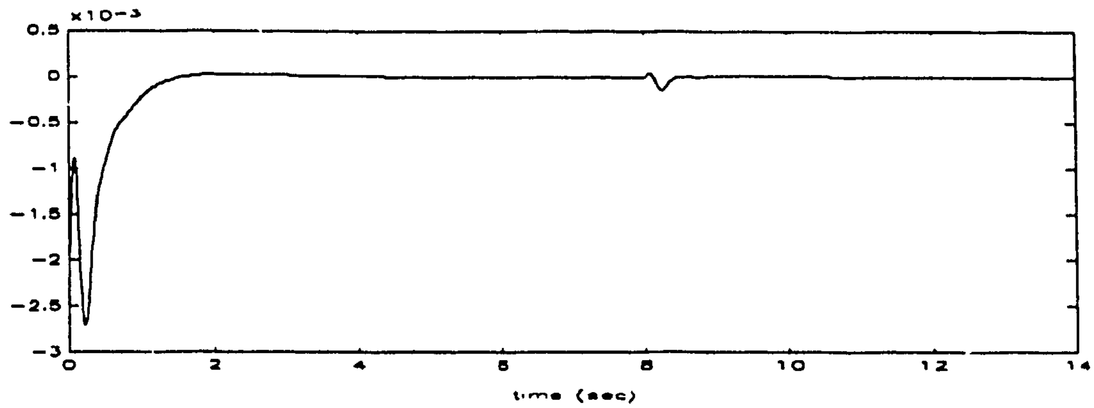

Fig. 35: Speed error with friction parameter changed by 1.5 times

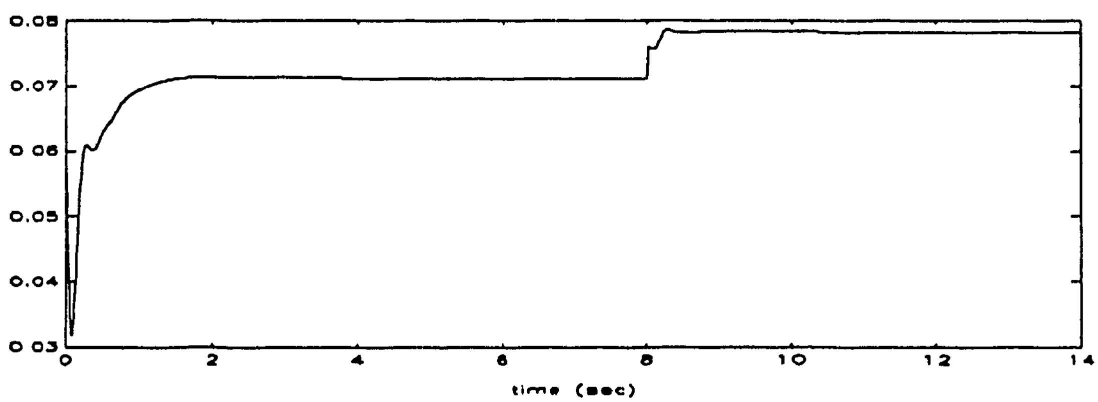

Fig. 36: Plant reference u_1 with friction parameter changed by 1.5 times

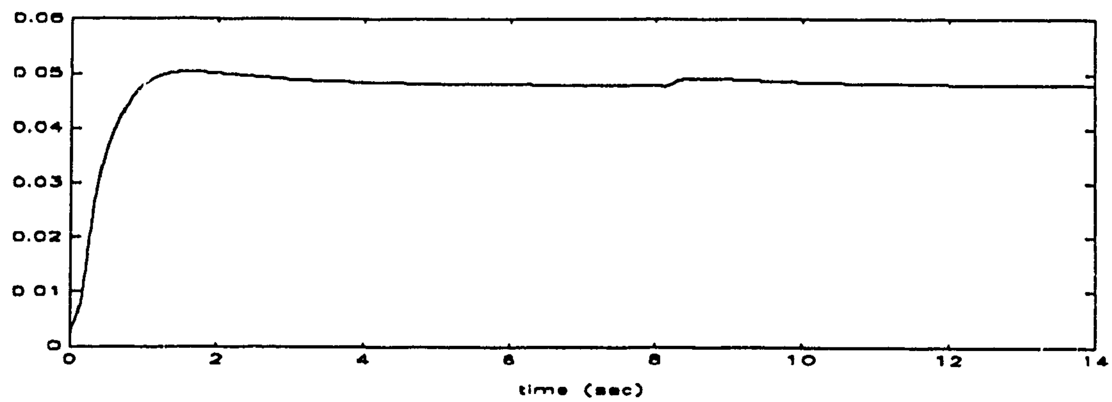

Fig. 37: Adaptive control parameter k_0 with parameter B changed by 1.5 times

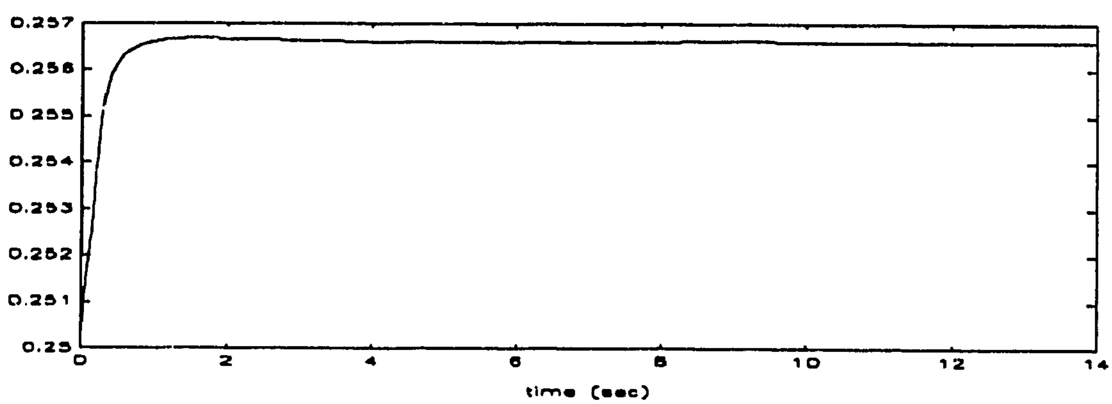

Fig. 38: Adaptive control parameter c_1 with parameter B changed by 1.5 times

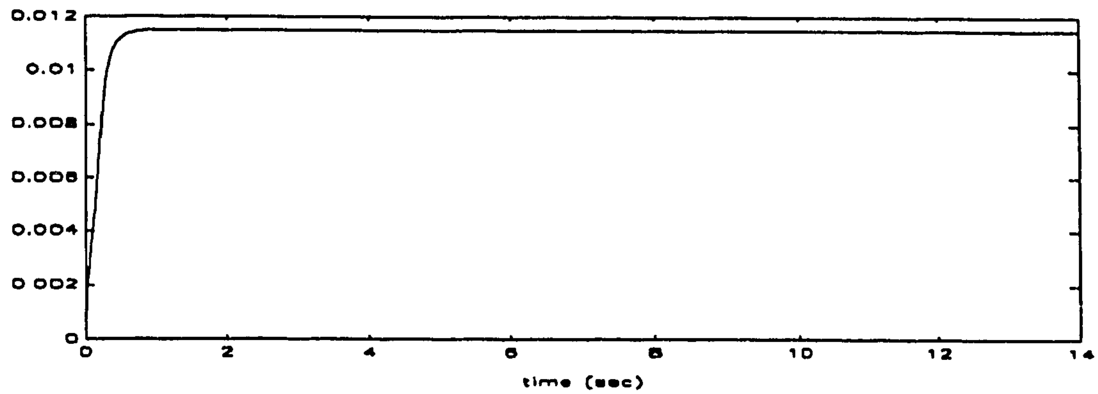

Fig. 39: Adaptive control parameter d_0 with parameter B changed by 1.5 times

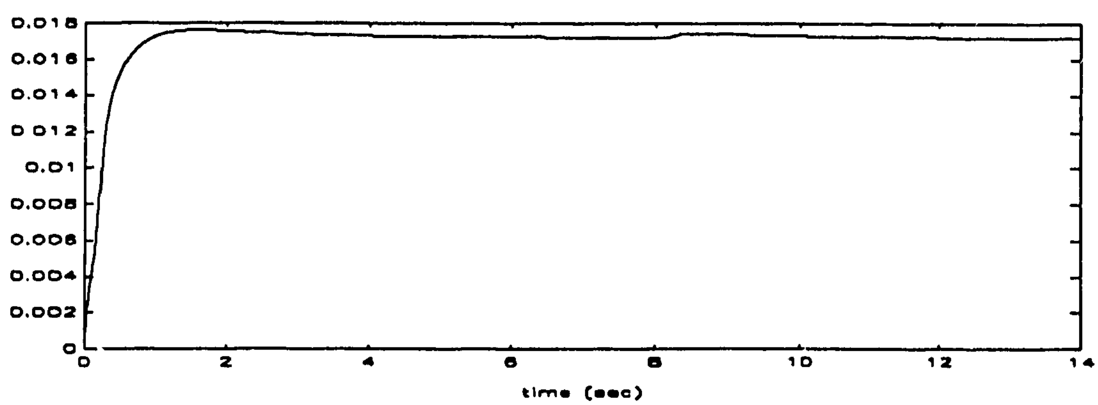

Fig. 40: Adaptive control parameter d_1 with parameter B changed by 1.5 times

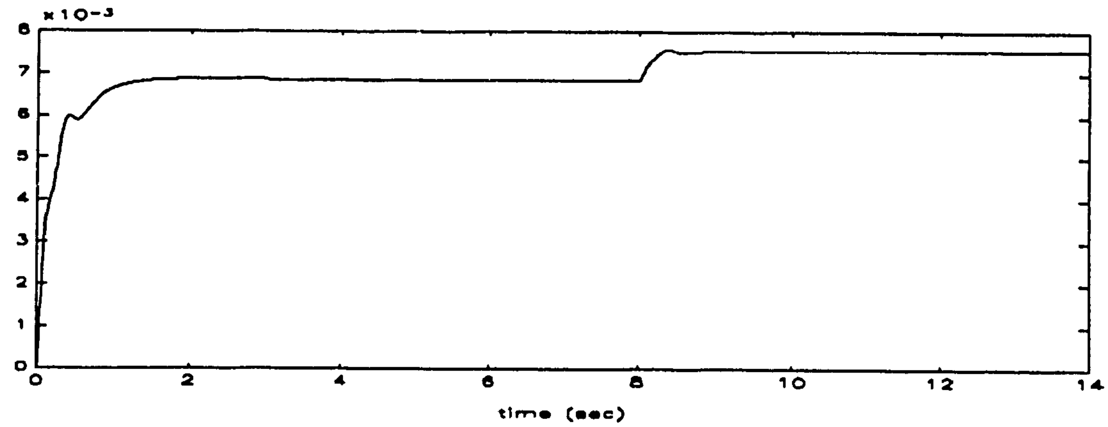

Fig. 41: Speed response with the parameters R_a,B and $K_a\Phi$ changed by 1.5 times

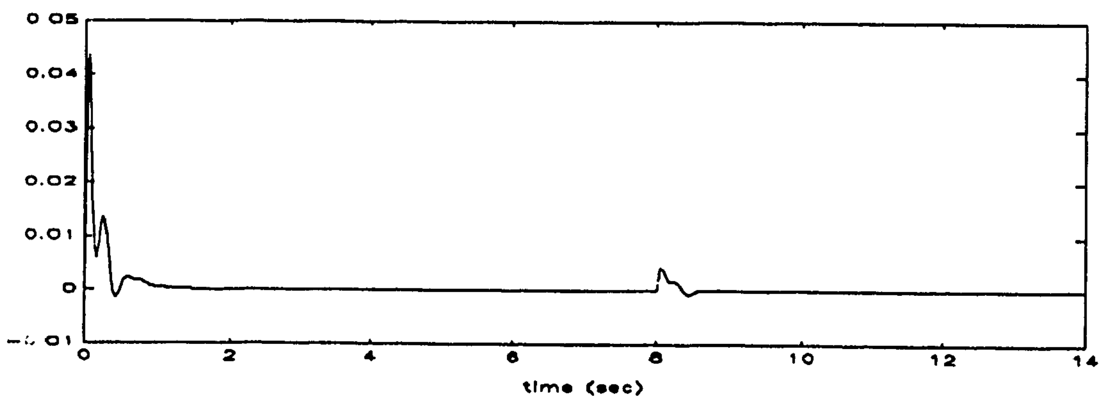

Fig. 42: Acceleration with the parameters R_a,B and $K_a\Phi$ changed by 1.5 times

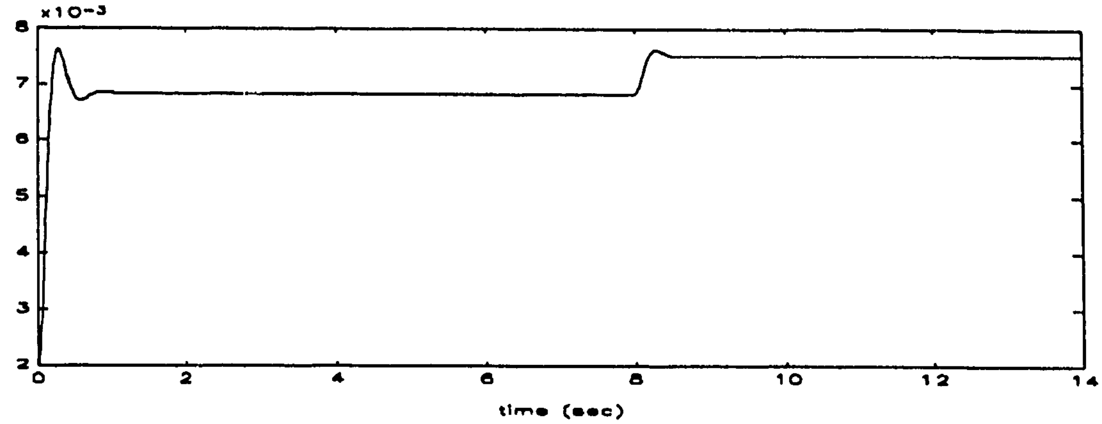

Fig. 43: Model speed response with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

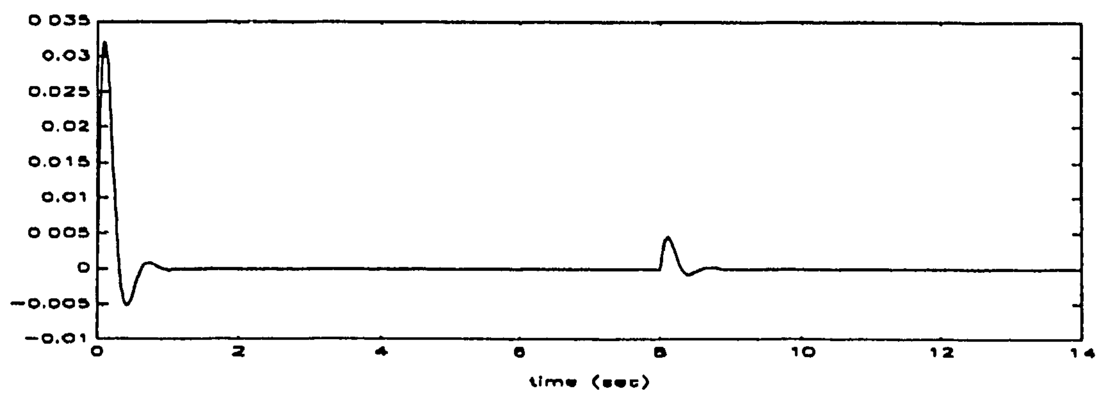

Fig. 44: Model acceleration with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

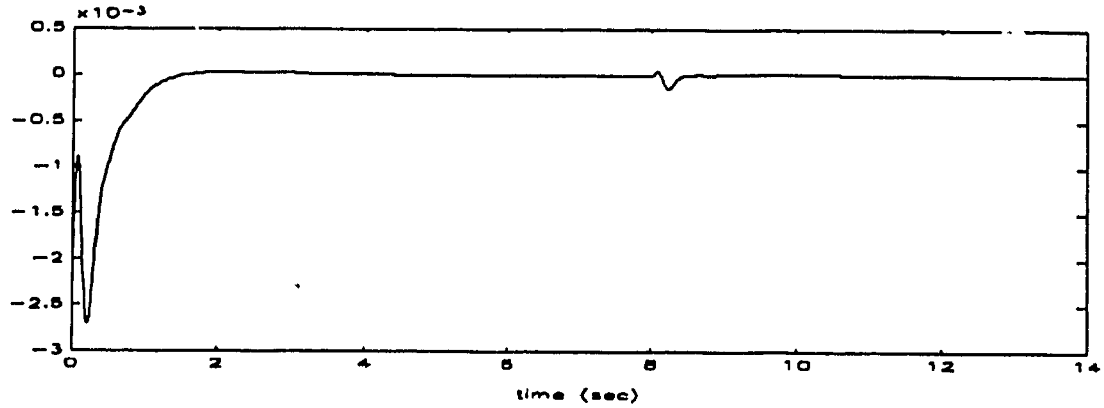

Fig. 45: Speed error with the parameters R_a, B and $K_a\Phi$ changed by 1.5 times

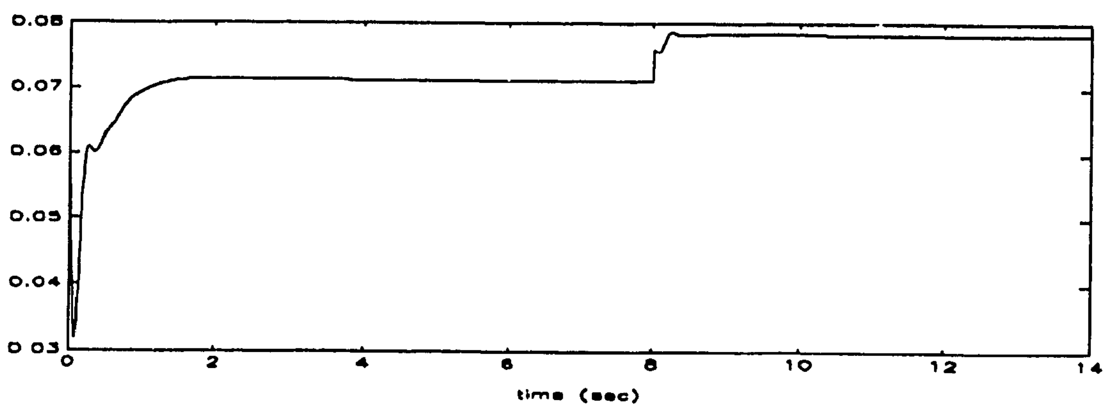

Fig. 46: Plant speed reference u_1 with parameters R_a, B and $K_a\Phi$ changed by 1.5 times

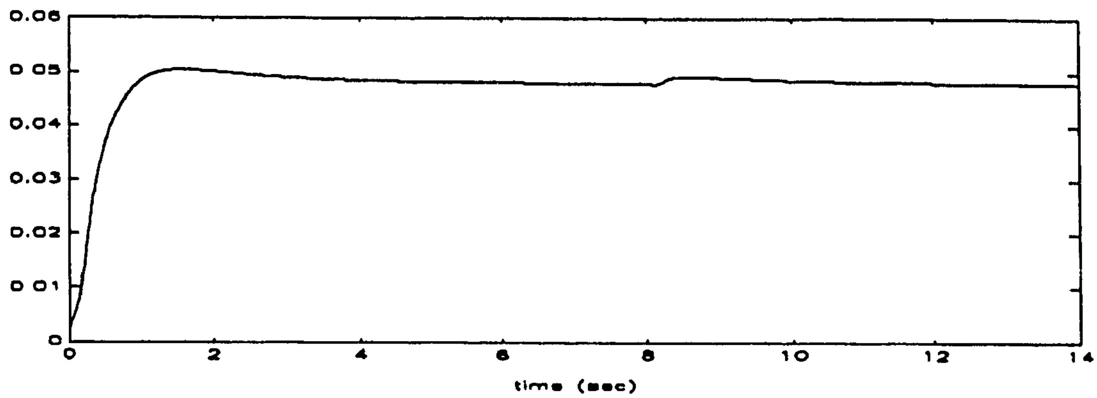

Fig. 47: Adaptive control parameter k_0 with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

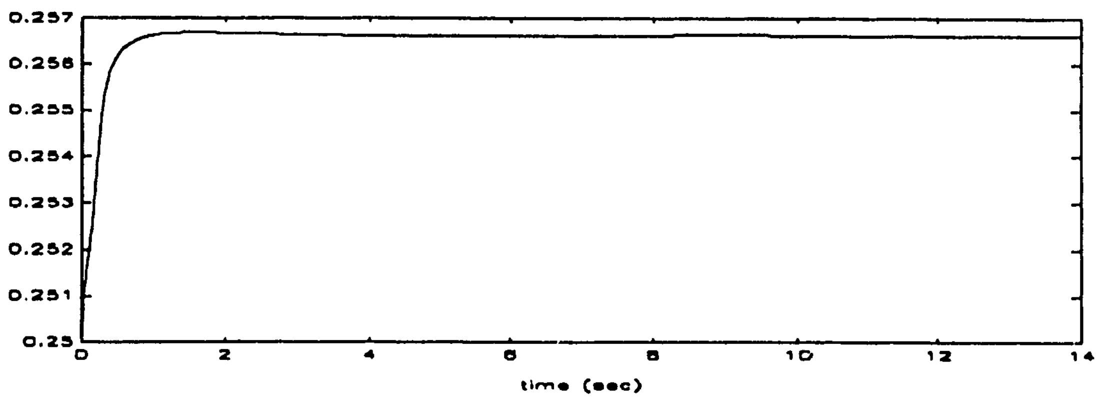

Fig. 48: Adaptive control parameter c_1 with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

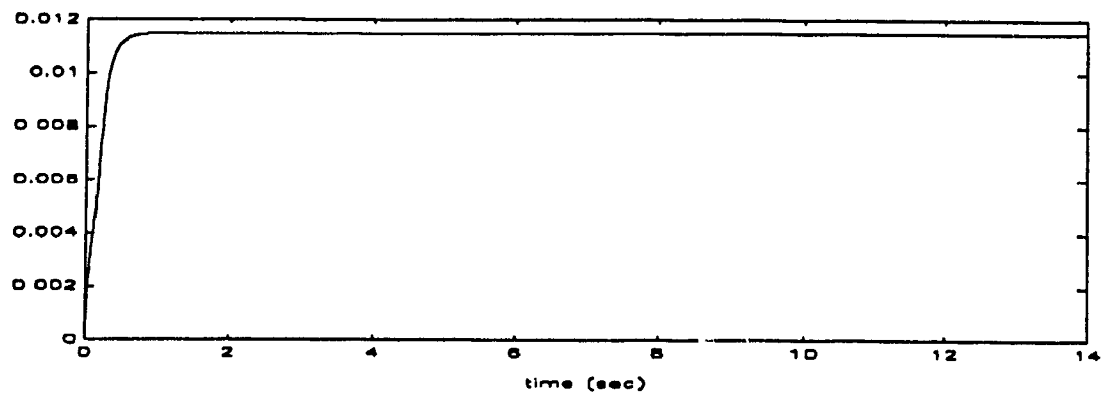

Fig. 49: Adaptive control parameter d_0 with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

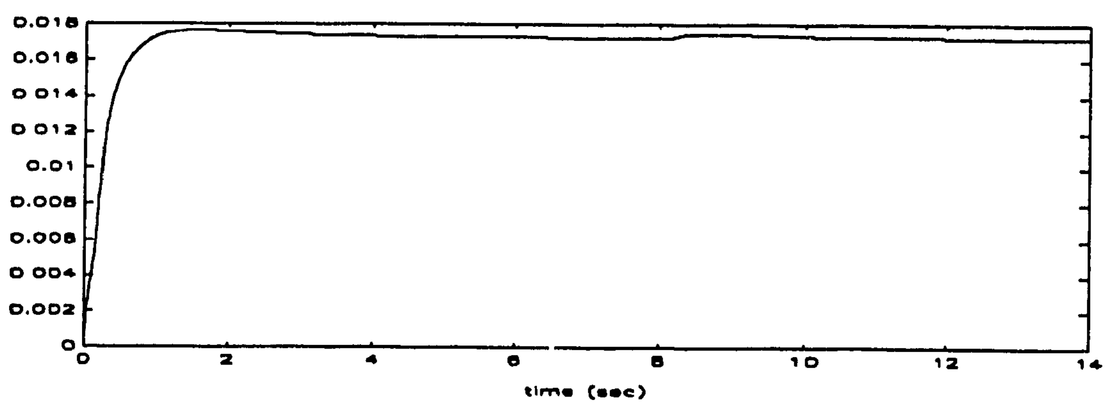

Fig. 50: Adaptive control parameter d_1 with parameters R_a,B and $K_a\Phi$ changed by 1.5 times

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