Minimum Variance Adaptive Control for Cutting Force in CNC Turning Machines

Mohamed M. Negm and A. M. Bassiuny

Abstract—**This paper proposes a synthesized method of a minimum variance adaptive control (MVAC) system to control the cutting force of the Computerized Numerical Control (CNC) turning machine. In this system a linearized state-space model for the CNC turning machine is derived, and a model reference adaptive system (MRAS), which includes the cutting force as a controlled output and the feed rate as a control input, is implemented. The deterministic autoregressive moving average (DARMA) model with auxiliary input is introduced to cope with any disturbances of the controlled system. The parameters of the DARMA model are obtained using the structure of a lattice adaptive control system. The robustness of the proposed controller copes with any changes in depth of cut and/or the cutting speed. These changes are embedded in the linearized model of the CNC machine and are considered as system parameters. Extensive computer simulations are made to prove the applicability of the proposed controller for controlling the cutting force over different operating conditions.**

Index Terms—**MVAC, reference model, lattice adaptive control factorization, cutting force, turning machine.**

I. Introduction

It is well known that control of the cutting force in machining is a challenging problem since the cutting dynamics varies significantly under normal operating conditions. The Computerized Numerical Control (CNC) machines are widely used in industry to overcome this problem, in addition to their ability to produce complex parts at high accuracy. However, the capital costs of CNC machines may be high and it is important, from economical point of view, to maintain the productivity of these machines at high level. This can be accomplished by maintaining the cutting force at a constant level. This also prevents the breakage of the cutting tool and regulates tool deflections that lead to geometric work-piece error. From control system point of view, maintaining the cutting force at a constant level during cutting process is not a simple matter. This is because of non-linearity and time varying behavior of the cutting process due to changes in depth of cut, spindle speed and material properties. During the past years, many research works have been carried out in the field of constant cutting force control. These works applied both conventional and adaptive control (AC) techniques. In machine tool control systems, AC is mainly divided into two classes: adaptive control constraints (ACC) and adaptive control optimization (ACO). ACC systems are designed to regulate the cutting force, torque, or power [1]. This type of control system is very important for industrial applications because it leads to better machine utilization. In ACO systems, the cutting conditions are determined by using a performance index, e.g. machining cost per unites volume of metal removed [2]. The application of this type is quite limited because of the difficulty of formulating a realistic performance index. Early research works in cutting force control were based on variable gain approach [3], [4]. In these works, the changes in the cutting conditions were represented as a change in the gain between the cutting force and the feed rate. An estimate of the process gain was used for adjusting the regulator parameter to ensure a constant loop gain in the presence of process variations. The main limitation of this approach is the requirements of prior information such as poles and zeros of the closed loops. A model reference adaptive control (MRAC) approach for controlling the turning operation is presented in [5]. The process dynamics was modeled as a first order system and the controller parameters were adjusted using gain adaptation algorithm. Implementation results of the previous two approaches demonstrated that the performance of the controller is sensitive to the selection of controller parameters. Moreover, the algorithm requires a prior knowledge for the selection of the polynomial of process dynamics. To overcome this problem, Fassois *et al.* in [6], presented an approach that requires no prior information, based on recursive estimation of machining process parameters. The turning process was modeled by an autoregressive moving average (ARMA) model. The proposed controller was composed of two loops; the first includes the process model and a controller designed based on pole placement technique and the second comprises the parameter estimator. The algorithm is quite simple since the non-linearity of process dynamics was neglected. The main idea of this system was to reduce the computational time. An eighth order dynamic model for the turning operation is introduced in [7]. The model was controlled utilizing a PI-controller in the feedback loop. The root locus method is used for tuning the controller parameters. Although the operating range covered only depths of cut between 0.635 mm and 1.905 mm, the results demonstrated that the system performance is influenced by these variations. Furthermore, the non-linear term of feed was not considered. Chen and Chang, [8], divided the nonlinear and time varying term of the cutting process into an average value and a non-linear perturbation. The process was controlled using a constant parameter PI-controller. The performance of the system was investigated using depths of cut that varies between one and 3 mm and the cutting speed were kept constant at 600 rpm. Although the cutting speed is not optimum since the cutting tool or

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material may change, the results showed large overshoots and steady-state error. Application of several adaptive control systems in machine tools is discussed in [1]. The non-linearity of the process model was divided into a linear system and a third order static feed equation. Although a significant improvement was achieved, oscillatory behavior of the system output could be observed. Allen *et al.*, [9], employed a self-tuning strategy to adapt cutting force controller. A second order ARMA model was used and a generalized minimum variance controller was implemented. The results indicated a slow dynamic response of the system and a considerable increase in the system overshoot as the depth of cut changes. Harder and Izakson, [10], modeled the process dynamics as a non-linear first order system with time-variable parameters, while the dynamics of feed drive was neglected. Two approaches to design a PI controller based on internal model control were described. In the first approach, the force was linearized around the operating point and a conventional PI controller was applied. The operating point, however, may change in large steps and consequently change the gain of the linearized model. The second approach introduced logarithmic transformation for linearization and the controller was designed based on a constant-gain system. Although both of these two approaches seem to be promising for implementation, the presented results showed some instability of the closed loop system as the cutting speed changed. In [11] major adaptive control constraint system is described. The application of these systems to constant force control was discussed. It is also interesting to mention that other systems have been developed based on new techniques such as neural network [12], [13], and fuzzy logic [14]-[16]. Developed performance for a CNC turning machine is given in [17]. In this paper a linearized state-space model for CNC turning machine is synthesized and a model reference adaptive control system is implemented. A minimum variance adaptive controller is designed to maintain the cutting force at a prescribed level by adjusting the feed rate. The robustness and applicability of the proposed controller under different variable cutting conditions is investigated via extensive computer simulations.

II. Turning Process Modeling

The dynamic model of the turning machine including the servo system, feed relation and cutting process dynamics is written as follows [8],

$$\begin{aligned} &\ddot{v}_f(t) = 2\xi\,\omega_n \dot{v}_f(t) + \omega_n{}^2 v_f(t) = k_m u(t) \\ &f(t) = T_n v_f(t) \\ &0.5 T_n(t)\dot{F}_c(t) + F_c(t) = a(t) k_f f(t)^p \end{aligned} \tag{1}$$

where

$v_f(t)$: feed rate of the cutting tool (mm/sec),

$u(t)$: input of the servo system (radian),

$f(t)$: feed (mm/rev),

$F_c(t)$: cutting force (N),

ξ, ω_n : damping ratio and angular natural frequency (rad/sec), of the servo system, respectively,

$T_n = 60/n$: revolution period of spindle (sec.),

n : spindle speed (rpm),

$a(t)$: depth of cut (mm),

k_m : constant of the servo system (mm rad/sec^3),

k_f : specific cutting force (N/mm^2),

p : a constant fraction <1.

The state-space model of (1) can be derived after factorizing $f(t)^p$, as given in (2)-(3).

$$\dot{\mathbf{x}}(t) = \mathbf{A}_0\mathbf{x}(t) + \mathbf{B}_0 u(t) + \mathbf{E}_0 \tag{2}$$

$$y_f(t) = f(t)^p = f(t) \pm \Delta f(t) \tag{3}$$

where

$$\mathbf{x}(t) = [F_c(t)\ f(t)\ \dot{f}(t)\ y_f(t)]^{\mathrm{t}};\ u(t) = u_s(t)$$

$$\mathbf{A}_0 = \begin{bmatrix} \frac{-2}{T_n} & 0 & 0 & \frac{2k_f a}{T_n} \\ 0 & 0 & 1 & 0 \\ 0 & -\omega_n^2 & -2\xi\omega_n^2 & 0 \\ 0 & c_1 & c_2 & c_3 \end{bmatrix};\ \mathbf{B}_0 = \begin{bmatrix} 0 \\ 0 \\ k_m T_n \\ 0 \end{bmatrix}$$

$$\mathbf{E}_0 = [0\ \ 0\ \ 0\ \ c_4]^{\mathrm{t}}.$$

The symbols c_1, c_2, c_3, and c_4 are constants and a is the depth of cut, which depends on the operating point, while $\Delta f(t)$ is the incremental change of the feed such that $\Delta f(t) = 0$ if $p = 1$, and the superscript "t", denotes the transposition. The discrete state-space model of system (2)-(3) is given by,

$$\mathbf{x}(k+1) = \overline{\mathbf{A}}\mathbf{x}(k) + \overline{\mathbf{B}}u(k) + \overline{\mathbf{E}} \tag{4}$$

where $\mathbf{x}(k)$ and $u(k)$ are the state-variable and input variable, respectively, while k denotes kT and T is the sampling period. The output vector is:

$$y(k) = k_d F_c(k) = \mathbf{C}\mathbf{x}(k) \tag{5}$$

where k_d is the dynamometer gain (N^{-1}), and $\mathbf{C} = [k_d\ 0\ 0\ 0]$.

III. Model Reference Adaptive System

The main innovation of the model reference adaptive system MRAS, is the presence of a reference model which specifies the desired performance of the CNC turning machine. The output of the reference model is compared with the actual measured cutting force. The error is fed into the proposed adaptive algorithm that is designed to assure stability of the MRAS. In this paper the proposed model reference includes the cutting force as a controlled output and the feed rate as a controlled input. A deterministic autoregressive moving average DARMA model with auxiliary input is introduced to the adaptive system to cope with any disturbances of the CNC controlled system. The parameters of this model are given by a lattice structure of the adaptive system to match the internal dynamics of the machine [18]. The DARMA model of the system (4), is given by [19]:

$$A(q^{-1})y(k) = B(q^{-1})u(k-d) + g \tag{6}$$

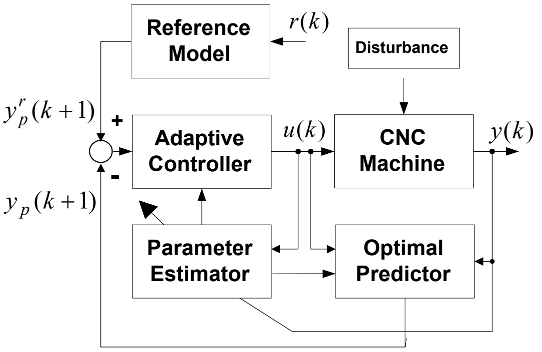

Fig. 1. MVAC system of the CNC turning machine.

where

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + ... + a_n q^{-n}$$

$$B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} + ... + b_{n-1} q^{-n+1}$$

The delay of the CNC adaptive system is d, and g is added to compensate for any changes in the depth of cut or spindle speed [17]. The symbol q^{-n} denotes the backward shift operator of order n. Now, let the desired cutting force of the CNC turning machine, $y^r(k) = k_d F_c^r(k)$; (output signal), satisfies the following reference model:

$$E(q^{-1}) y^r(k) = q^{-d} g' H(q^{-1}) r(k) \quad (7)$$

where g' is a constant gain, and

$$H(q^{-1}) = 1 + h_1 q^{-1} + h_2 q^{-2} + ... + a_m q^{-m}$$

$$E(q^{-1}) = 1 + e_1 q^{-1} + e_2 q^{-2} + ... + e_m q^{-m} .$$

When the CNC system is driven by $r(k)$, it is desirable to apply feedback to the system so that the output will be equal to that of the reference model by the same input. Hence the system (7) may be expressed in the following predictor form, [20]:

$$E(q^{-1}) y(k+d) = \alpha(q^{-1}) y(k) + \beta(q^{-1}) u(k) + h(q^{-1}) \quad (8)$$

where

$$\alpha(q^{-1}) = G(q^{-1}), \ \beta(q^{-1}) = F(q^{-1}) B(q^{-1}),$$

$$h(q^{-1}) = q^d F(q^{-1}) g$$

and

$$E(q^{-1}) = F(q^{-1}) A(q^{-1}) + q^{-d} G(q^{-1})$$

$$F(q^{-1}) = 1 + f_1 q^{-1} + f_2 q^{-2} + ... + f_{d-1} q^{-d+1} \quad (9)$$

$$G(q^{-1}) = g_0 + g_1 q^{-1} + g_2 q^{-2} + ... + g_{n-1} q^{-n+1}$$

The coefficients of the polynomial $\alpha(q^{-1}), \beta(q^{-1})$, $h(q^{-1}), E(q^{-1})$, and $H(q^{-1})$ are calculated from the lattice structure of the adaptive control system [21], while that of the polynomials $F(q^{-1})$ and $G(q^{-1})$ can be calculated by expanding (9). For one step ahead predictor, $d = 1$:

$$F(q^{-1}) = 1, ..., \beta(q^{-1}) = B(q^{-1})$$

$$h(q^{-1}) = qg, ..., \alpha(q^{-1}) = q[E(q^{-1}) - \alpha(q^{-1})]$$

Accordingly, the one step ahead predictor can be written from (8) as follows:

$$\hat{y}(k+1) = \hat{\boldsymbol{\theta}}(k)^{\mathrm{t}} \boldsymbol{\varphi}(k) \quad (10)$$

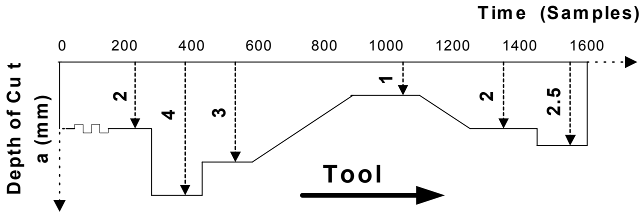

Fig. 2. Profile of work-piece used in simulation.

where the symbol $\hat{y}$ denotes the estimated value of y; etc., and

$$\hat{\boldsymbol{\theta}}(k)^{\mathrm{t}} = [\hat{\alpha}_1, \hat{\alpha}_2, ..., \hat{\alpha}_n;\ \hat{\beta}_1, \hat{\beta}_2, ..., \hat{\beta}_n;\ \hat{h}]$$

$$\hat{\boldsymbol{\varphi}}(k)^{\mathrm{t}} = [y(k), y(k-1), ..., y(k-n+1); \\ u(k), u(k-1), ..., u(k-n+1); 1]$$

The parameters of the predictor model (10) can be estimated by the following least squares algorithm, [19]

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \frac{\mathbf{P}(k-2)\boldsymbol{\varphi}(k-1)[\mathbf{y}(k) - \boldsymbol{\varphi}(k-1)^{\mathrm{t}} \hat{\boldsymbol{\theta}}(k-1)]}{\gamma_1/\gamma_2 + \boldsymbol{\varphi}(k-1)^{\mathrm{t}} \mathbf{P}(k-2) \boldsymbol{\varphi}(k-1)} \quad (11)$$

$$\mathbf{P}(k-1) = \mathbf{P}(k-2) + \frac{\mathbf{P}(k-2)\boldsymbol{\varphi}(k-1)\boldsymbol{\varphi}(k-1)^{\mathrm{t}} \mathbf{P}(k-2)}{\gamma_1/\gamma_2 + \boldsymbol{\varphi}(k-1)^{\mathrm{t}} \mathbf{P}(k-2) \boldsymbol{\varphi}(k-1)} \quad (12)$$

where

$\theta(0) = \theta_0;\ P(-1) = P_0;\ 0 < \mathrm{P} \le \infty;\ 0 < \gamma_1 \le 1;\ 0 < \gamma_2 \le 2$.

The minimum variance adaptive control (MVAC) of the CNC turning machine given in (13), $u(k)$, can be derived by minimizing the following performance index J_n and satisfying (11), [21].

$$J_n = \left\| E(q^{-1})[y(k+1) - y^r(k+1)] \right\|_Q^2 + \left\| u(k) \right\|_R^2$$

$$u(k) = [\hat{\beta}_0^t Q \hat{\beta}_0 + R]^{-1} \hat{\beta}_0 Q [g' H(q^{-1}) r(k) - \\ \hat{\alpha}(q^{-1}) y(k) - [\hat{\beta}(q^{-1}) - \hat{\beta}_0] u(k) - \hat{h}(q^{-1})] \quad (13)$$

where $\| . \|$ denotes the norm value, while $Q > 0$ and $R \ge 0$ are the weight matrices. The MVAC system structure is implemented using (13) as shown in Fig. 1, where the predicted output is given by,

$$y_p(k+1) = E(q^{-1}) y(k+1) \quad (14)$$

Note that the desired value of $y_p(k)$ is $y_p^r(k)$, which is corresponding to the reference signal $r(k)$.

IV. Simulation Results

The performance of the proposed MVAC system is investigated with the turning process by changing the depth of cut of the work-piece under constant or variable cutting force. First the work-piece is skewed by ±0.5 mm and then the depth of cut is increased stepwise from 2 to 4 mm, then decreased stepwise from 4 to 3 mm. This is followed by a linear ramp to 1 mm and increased to 2 mm and finally a stepwise increase from 2 to 2.5 mm. The profile of the work-piece is shown in Fig. 2, where the upper area depicts the cut, while the time is written in samples horizontally. During the simulation, the material properties are kept constant, i.e. $k_f = 1732$ N/mm^2, while the cutting speed changes between 600 and 1800 rpm. No restrictions were made on the control signal. The remaining data used in the

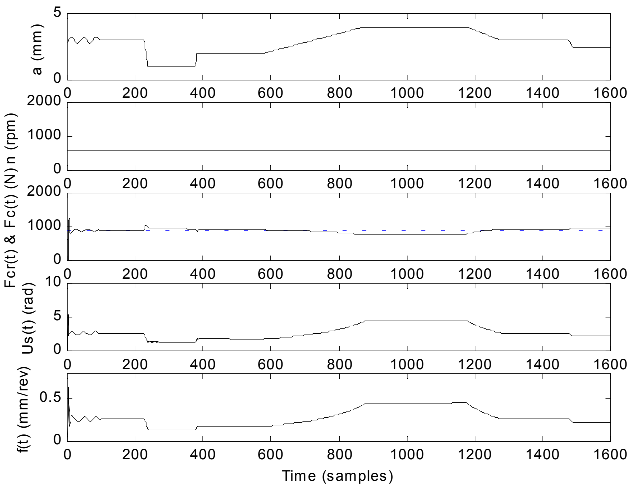

Fig. 3. Response of the proposed CNC control system, ($n(t) = 600$ rpm, $p = 1.0$); $P_0 = 20250$, $\gamma_1 / \gamma_2 = 1.0$.

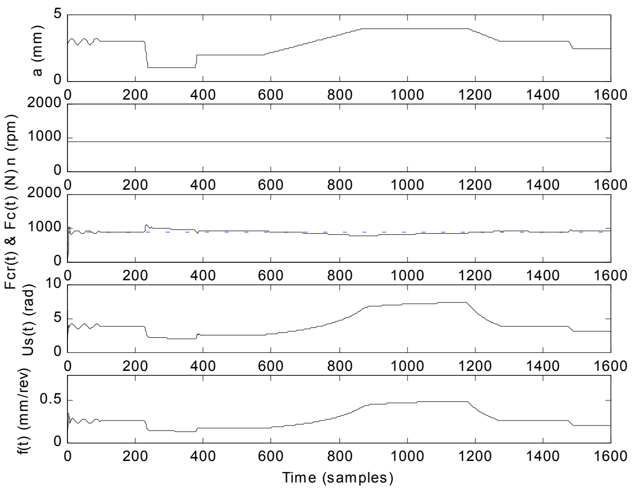

Fig. 4. Response of the proposed CNC control system, ($n(t) = 900$ rpm, $p = 1.0$); $P_0 = 1000$, $\gamma_1 / \gamma_2 = 0.667$.

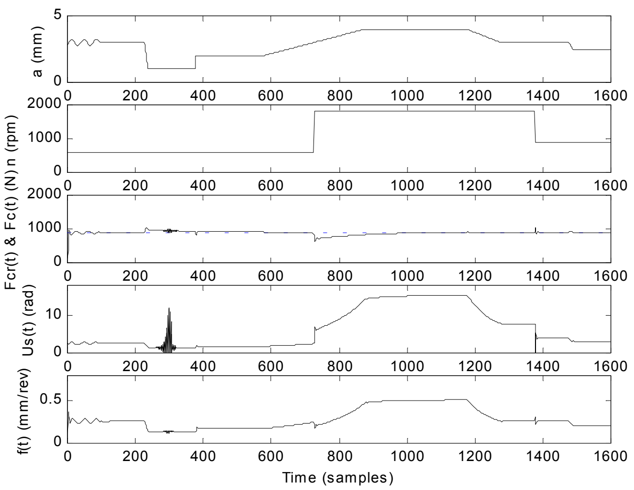

Fig. 5. Response of the proposed CNC control system, (n is variable, $p = 1.0$); $P_0 = 20250$, $\gamma_1 / \gamma_2 = 80$.

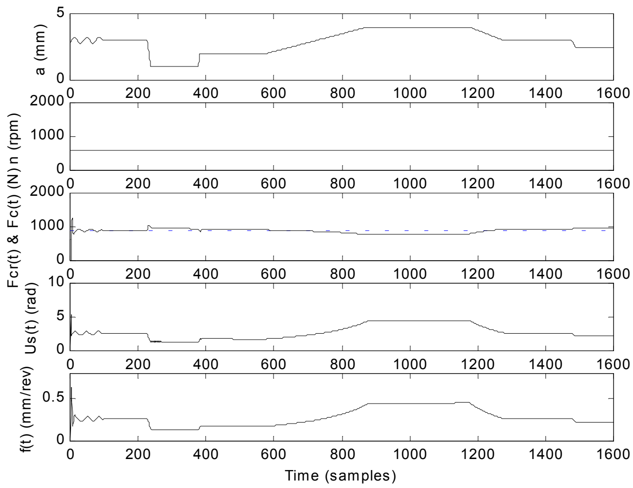

Fig. 6. Response of the proposed CNC control system, (n and F_c are variables, $p = 1.0$), $P_0 = 1000$, $\gamma_1 / \gamma_2 = 0.769$.

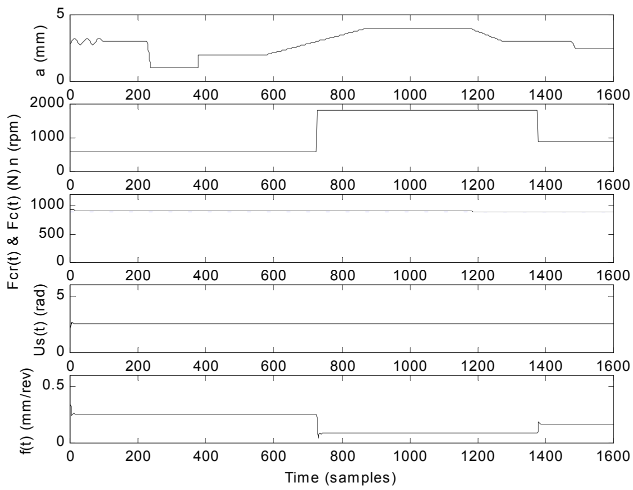

Fig. 7. Response of the proposed CNC control system, (n is variable, $p = 0.85$); $P_0 = 75000$, $\gamma_1 / \gamma_2 = 10^6$.

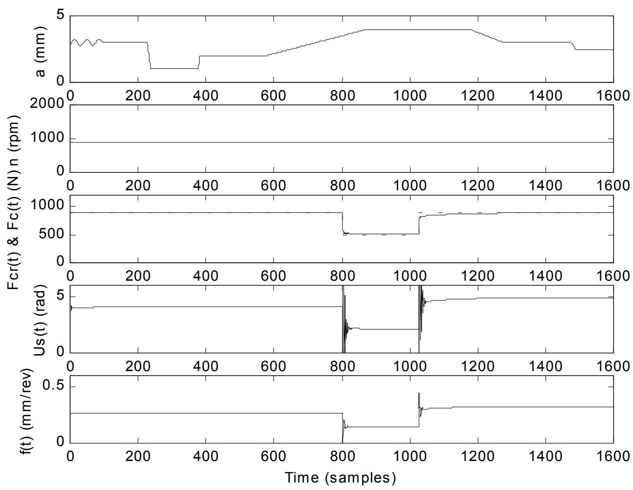

Fig. 8. Response of the proposed CNC control system, (n and F_c are variables, $p = 0.85$), $P_0 = 10^5$, $\gamma_1 / \gamma_2 = 10^6$.

simulation are given by: $k_d = 4$ N^{-1}, $\xi = 0.42$, $\omega_n = 36$ rad/sec, $k_m = 1296$ mm.rad/sec^3.

The desired cutting force is limited to 900 N, and may be reduced to 500 N. The applicability of the proposed controller is investigated in two cases. Firstly, the incremental change of feed $\Delta f(t)$ in (3) is taken into consideration and the process is treated as a non-linear system ($p = 0.85$), while $\Delta f(t)$ is neglected, i.e. $y_f(t) = f(t)$, in the second case, which represents the linear system ($p = 1$). The simulation results shown in Figs. 3 to 8, are obtained based on the MVAC given by (13), using sample time $T = 0.02$ sec. The vertical lines of these figures show from up to down the cutting area $a(t)$ in mm, the cutting speed $n(t)$ (rpm), the desired cutting force $F_c^r(t)$ (N) in dotted line and its response $F_c(t)$ (N) in solid line, the control input $u_s(t)$ (radian) and finally the feed $f(t)$

(mm/rev). The horizontal lines illustrate the time in samples. Figs. 3 to 6, illustrate the results of the developed MVAC on the linear system, while Figs. 7 and 8, are given for the nonlinear system. The controller parameters for Figs. 3 to 6 are $q = 10^6$ and $r = 1.0$, while for Figs. 7 and 8 are $q = 10^6$ and $r = 0.001$. The other controller parameters are selected according to the desired performance as written on these figures. Fig. 3 shows the system performance when the cutting speed was set at 600 rpm, while in Fig. 4, was 900 rpm. Moreover, the desired cutting force was maintained constant at 900 N. The results show a well-tuned behavior with a good transient response and high robustness for both the cutting force and feed over the range of depth of cut. In contrast, the previous work in [8], showed instability of the PI-controller due to changes in the depth of cut. Furthermore, the results given by Harder and Isaksson, [10], showed that the regulator must be adapted in each case when the cutting speed changes. Otherwise the closed loop system might become unstable. However, good agreement between the desired and measured cutting force are observed.

The tracking capability of the MVAC system over the whole range of changes in the cutting speed and depth of cut is shown in Fig 5. Fig. 6 illustrates the performance with the changes in both the depth of cut and cutting speed. It can be observed that the proposed controller has the best robustness and adapts well for the whole process when dealing with a linear system. However, the system also works well in the case when dealing with the non-linearity of the feed as demonstrated in Figs. 7 and 8. In Fig. 7 the speed is changed from 600, 1800 to 900 rpm while keeping the desired cutting force constant at 900 N. Fig. 8 depicts the performance with constant cutting speed of 900 rpm, while the cutting force is changed between 900 N and 500 N. The results presented in Figs. 5, 6 and 8, depict some oscillatory behavior during the turning process at different depth of cut. Adjusting the forgetting factors γ_1, γ_2 and P_0 of the MVAC system, can eliminate these oscillations. The cutting force is rather well regulated at the desired value of the desired cutting force $F_c^r(t)$. The feed rate is adjusted by the MVAC to compensate for the changes in cutting speed and depth of cut. The results also reveal that the behavior of feed rate differs to some extent from that shown in Fig. 5. As demonstrated by the given simulation results, coincidental regulating response is achieved using the proposed MVAC in case of linear system ($p = 1$) and nonlinear system $p = 0.85$ and $p = 1$, but at the expense of the control input and feed in the latter.

V. Conclusions

As well known, constant cutting force aims to increase productivity, increase metal removal rate, and to avoid tool breakage. Therefore, in this work a MVAC system is designed to maintain a constant cutting force over the whole control range of the turning process. The system incorporates a detailed process model and employs a factorization method to linearize the feed relation. The parameters of the system model are given by the lattice structure of the adaptive system to match the internal dynamics of the machine. An MRAS is designed based on the minimum variance control strategy and provide effective control and good regulation of both the cutting force and the machine feed rate. Coincidental response between the desired cutting force and its measured value is achieved in spite of the changes in depth of cut and/or spindle speed. The results demonstrate the robustness and feasibility of the proposed controlled system in case of variable cutting conditions.

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