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DESIGN OF AN INDUSTRIAL GRINDING MACHINE PROCESS CONTROLLER USING MATLAB

Uebari Barisuka*[1], Akoba Bright[2], Anthony Jacob Eke[3]

[1,2]Department of Electrical and Electronic Engineering, Kenule Saro-Wiwa Polytechnic, Rivers State, Nigeria.

[3]Department of Electrical and Electronic Engineering, Federal Polytechnic Ngodo, Isuochi, Nigeria.

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***Corresponding Author: Uebari Barisuka**
Department of Electrical and Electronic Engineering, Kenule Saro-Wiwa Polytechnic, Rivers State, Nigeria.

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ABSTRACT

The efficiency of industrial grinding machines is improved by using a dynamic model that captures most of the system's key characteristic parameters.in this paper, a good model of the industrial grinding machine was developed where the infeed velocity is considered amongst the goals in manufacturing, one of the commonest is to improve the quality and accuracy of the parts being fabricated without reducing productivity. This places a very high-performance demand on industrial machine tools. An industrial grinding machine is a typical example where adequate control of the process to improve efficiency and maximize productivity is required. But the presence of some transmission components induces wear, high friction, and other errors especially inadequate control which can be a limiting factor to the efficiency of an industrial grinding machine operation. This research is aimed at investigating the poor performance of an industrial grinding machine as well as designing a suitable controller to improve the grinding machine operation. Moreover, an appropriate controller that ensures stable control of the grinding machine with less than 5 percent overshoot, 1.6 second settling time and a rise time less than 5 seconds to a unit step input has been achieved.

KEYWORDS: Grinding Machine, industrial machines, process controller, Grinding controller, High speed machine.

INTRODUCTION

Grinding is the process of removing metal by the application of abrasives which are bonded to form a rotating wheel. When the moving abrasive particles contact the workpiece, they act as tiny cutting tools, each particle cutting a tiny chip from the workpiece (QiulinXieI,2008). A grinding machine, often shortened to grinder, is any of various power tools or machine tools used for grinding, which is a type of machining using an abrasive wheel as the cutting tool (Wikipedia, 2007). Industrial grinding machines are used in many manufacturing processes. For instance, according to R. P. King (1999), industrial grinding machines used in the mineral processing industries are mostly of the tumbling mill type. These mills exist in a variety of types - rod, ball, pebble autogenous and semi-autogenous. Another example is the high-speed grinding (HSG) machine. As explained by KopacJanez and Krajnick (2006), the meaning of HSG is twofold: (1) A high-productivity grinding as traditional processes and (2) it can also be a material removal rate. The grinding machine is used for roughing and finishing flat, cylindrical, and conical surfaces; finishing internal cylinders or bores; forming and sharpening cutting tools; snagging or removing rough projections from castings and stampings; and cleaning, polishing, and buffing surfaces. Some grinding applications, such as ball and roller bearings, pistons, valves, cylinders, cams, gears, cutting tools and dies, etc (QiulinXieI, 2008).

Globally, the accuracy and cycle time demands on high precision machine tools are growing at a significant rate as manufacturers seek to gain a competitive advantage (Del Re *et al.*, 1996). The efficiency of industrial grinding machines is improved by using a dynamic model that captures most of the system's key characteristic parameters. (Stephens *et al*., 2010).

MATHEMATICAL MODELLING

Figure 1 shows an improved cylindrical grinding machine with infeed velocity V_s,the energy consumption associated with sliding and plowing are insignificant compared to chipping energy, and hence almost all energy is used for material removal and the threshold force can be ignored. Therefore, the grinding force can be modeled to be proportional to the material removal rate.

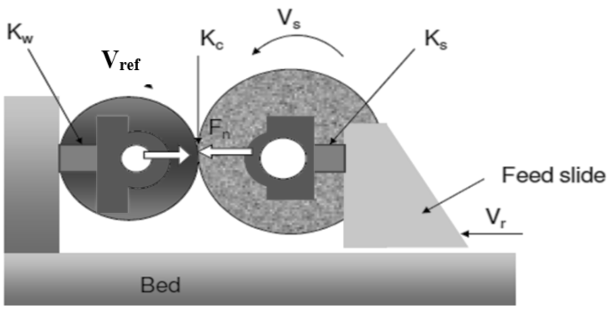

Figure 1: Schematic of cylindrical grinding machine.

The material removal can be computed as follow:

$$Q = \pi b_s d_w v_S \quad (1)$$

where Q is the material removal rate. b_s = the grinding wheel width, d_w = the diameter of workpiece , v_s = infeed velocity, and k_c= the effective stiffness. However, because of the final stiffness associated with work, wheel and contact, the actual radial infeed velocity will be different from the commanded radial infeed velocity. Neglecting wheel wear for the moment, continuity requires that the difference between the controlled u(t) and the actual infeed velocity V_s (t) be equal to the time rate change of the radial elastic deflection of the grinding system given by:

$$u(t) - V_s = \frac{F_n}{k_c} \quad (2)$$

$$\varepsilon = \frac{F_n}{k_c} \quad (3)$$

where F_n is the normal force component, and ε is the radial elastic deflection of the grinding system. For cylindrical plunge grinding with a constant radial speed, there is a relationship between the control feed rate V_r and the actual velocity V_{reff} as described by:

$$V_r - V_{reff} = \frac{d}{dt}\varepsilon \quad (4)$$

$$V_r = \frac{d}{dt}\varepsilon + V_{reff} \quad (5)$$

The control feed rate force F_r is obtained by applying Newton's Law to Equation (5) as defined by:

$$F_r = m\frac{d}{dt}V_r = m\left(\frac{d^2}{dt^2}\varepsilon + \frac{d}{dt}V_{reff}\right) \quad (6)$$

In Equation (6) above, m is the mass of the grinding wheel. The grinding normal force can be approximated to be proportional to the material removal rate as expressed in:

$$F_n = cQV_{reff} \quad (7)$$

where c is the proportionality constant describing the dullness of the grinding wheel.

Taking the Laplace transform of Equations (6) and (7) gives:

$$F_r(s)=m(\varepsilon s^2 + V_{reff}s) \quad (8)$$

$$F_n(s) = cQV_{reff} \quad (9)$$

Combining Equations (8) and (9), the transfer function of the machine from F_r to F_n can be obtained as follows:

$$G_p(s) = \frac{F_n(s)}{F_r(s)} = \frac{cQV_{reff}}{m(\varepsilon S^2 + V_{reff}S)} \quad (10)$$

The practical parameter values areV_{reff} = 0.40m/sec, the average dullness of the grinding wheel c = 0.165m/s, the material removal rate(Q) =68.18Kgm^3/s, the sandard mass of an industrial grinding wheel (m) = 12.35Kg, and ε =0.081. Substituting this values into Equation (10), transfer lunction of the machine is presented in Equation (11). The block diagram of the system is shown in Figure 2.

$$G_p(s) = \frac{4.5}{s(s+5)} \quad (11)$$

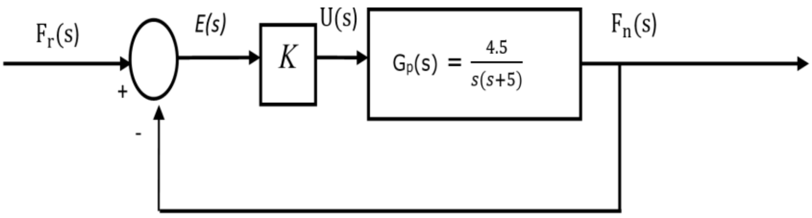

Figure 2: An industrial grinding machine control system.

CONTROL SYSTEM DESIGN

The main objective of this design is to use a controller with gain K to improve the performance of the industrial grinding process, whose transfer function is represented IN Equation (11). The design criteria are: settling time (with a 2% criterion) less than 1.6 second, percentage overshoot less than 5% to a unit step input, and rise time of less than 1 seconds to a unit step input.

The continuous-time closed-loop transfer function of the grinding machine was derived from Equation (11) using MATLAB and it is given by:

$$G_{cloop}(s) = \frac{4.5}{s^2 + 5s + 4.5} \quad (12)$$

A suitable proportional controller of gain K was designed using MATLAB control toolbox tuning, which will provide required system stability by meeting the design specification. Selecting the suitable controller gain K requires MATLAB tuning of the closed-loop transfer function using the control system toolbox as shown by the Bode plot in Figure 3.

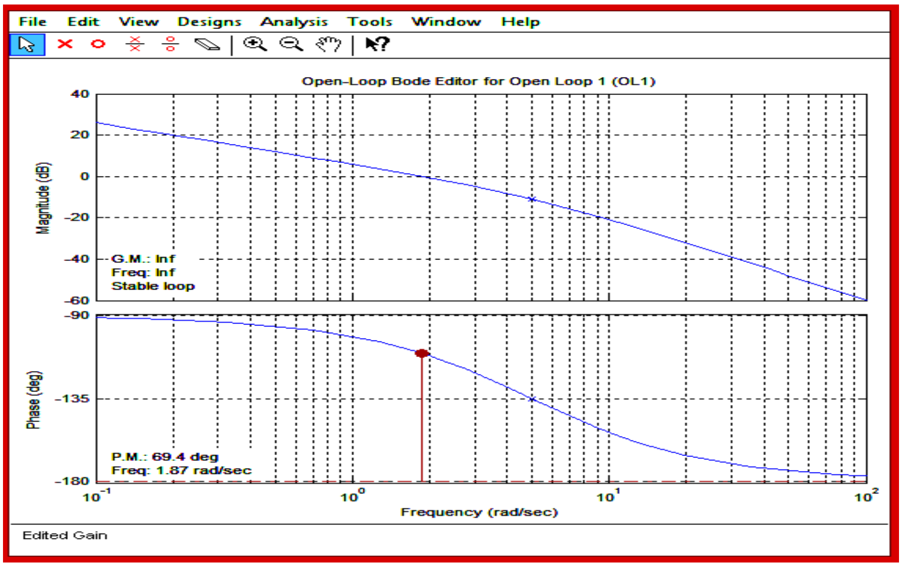

Figure 3: The Bode Plot of $G_{cloop}(s)$

From the Bode plot in Figure 3, Phase Margin (P.M.) = 69.4^0. The relationship between Damping Ratio and Phase Margin is given by:

Damping ratio, $\alpha = 0.01P.M.$ (13)

$$= 0.01*69.4 = 0.694$$

The crossover frequency $w_n = 1.87$rad/sec.

From Equation (12), the characteristic equation is expressed as:

$$1 + G_p(s)H(s) = s^2 + 5s + 4.5 = 0 \qquad (14)$$

where H(s) is the unity feedback whose value is 1. The equivalence of Equation (14) for a second order system is given by:

$$1 + G_p(s)H(s) = s^2 + 2\alpha w_n s + w_n^2 = 0 \qquad (15)$$

Comparing of Equations (14) and (15), the controller gain K is determined as in Equation (16). Adding the value of K to the control system as shown Figure 4, the closed-loop transfer function of the grinding machine and the controller gain K is given in Equation (17).

$$K = w_n^2 = (1.87)^2 = 3.51 \qquad (16)$$

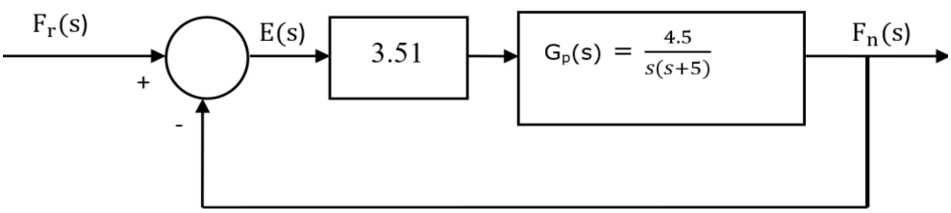

Figure 4: An industrial grinding machine system with designed controller.

$$G_c(s) = \frac{15.795}{s^2 + 5s + 15.795} \qquad (17)$$

Converting the transfer function in Equation (17) into discrete time model using MATLAB with a sampling period of Ts = 0.01, the discrete closed-loop transfer function of the system becomes:

$$G_c(z) = \frac{0.0007766\,(z+0.9835)}{z^2 + 1.95z + 0.9512} \qquad (18)$$

RESULTS AND DISCUSSION

The continuous-time, closed-loop step response of the system to unit step input is given by the simulated waveform shown in Figure 5. In this case the system was simulated without the designed controller and called uncompensated system.

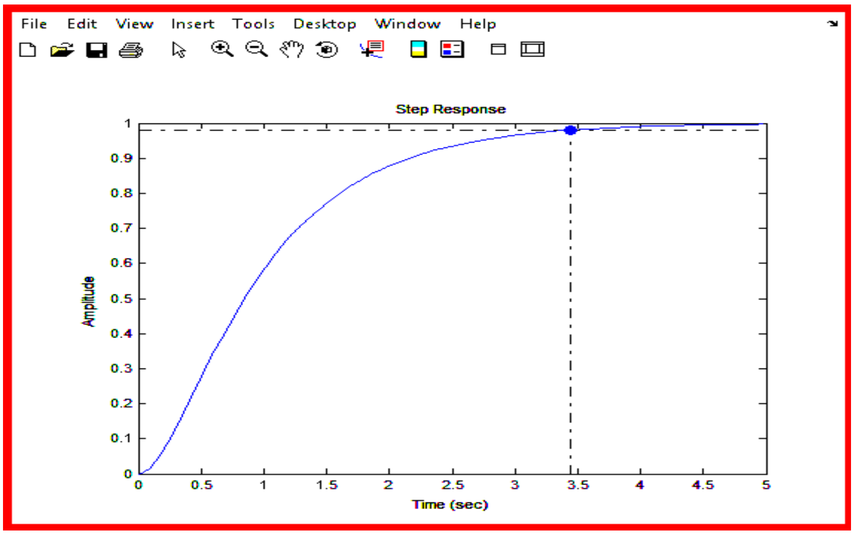

Figure 5: The unit step response of $G_{cloop}(s)$.

The settling time and other parameters as shown in Figure 5 revealed that that the system did not meet the desired performance specification. Also, in order to further test for the stability of the system, the Bode Plot $G_{cloop}(s)$ was carried out in MATLAB. The resulting frequency plot is shown in Figure 6.

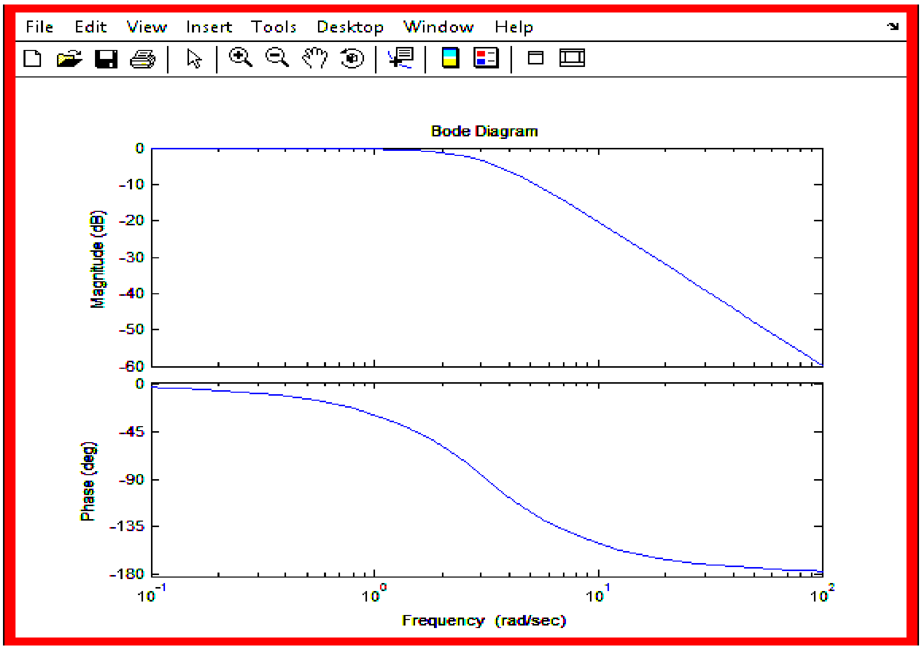

Figure 6: The Bode plot of uncompensated system.

From Figure 6, the Bode plot Gain Margin (GM) is negative and the Phase Margin (PM) is infinite. This defines an unstable system. Therefore, a suitable controller gain was required to achieve system stability by meeting the design specification. Then a closed-loop step response simulation conducted in terms of Equation (18) yielded the simulated step response waveform shown in Figure 7.

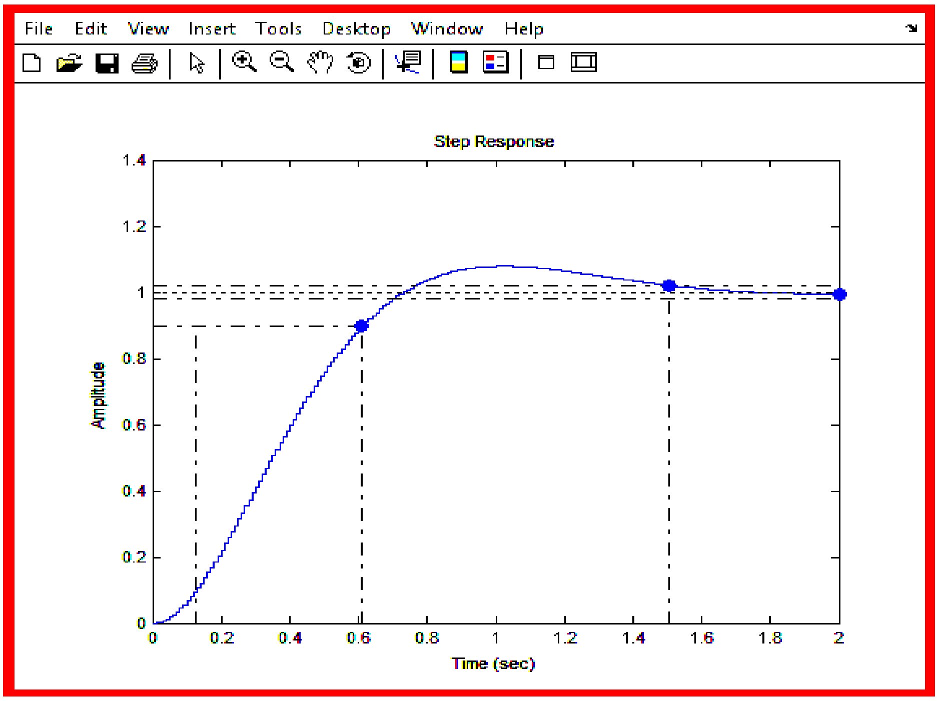

Figure 7: The step response plot of the compensated system.

ThePlot of $G_c(z)$ as shown in Figure 7 indicated that it is stable with settling time of 1.51 seconds and rise time of 0.6, and percentage overshoot of 4.81%. Hence, the designed sytsem met entire performance criteria required for effective operation in the industry.

CONCLUSION

The results of the Bode plot and the unit step response analysis as shown in Figure 7 revealed that the controller gain K introduced into the industrial grinding machine control system satisfactorily met the overall design specification. The specified settling time,the percentage overshoot, phase margin and other related parameter values required to bring the system to acceptable stability are achieved. Obviously, controller design has greatly improved the overall performance of the industrial grinding process.

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