# AN OPTIMIZATION APPROACH TO PREVENT CHATTER VIBRATIONS


[1]MEHMET ALPER SOFUOGLU, [2]FATIH HAYATI CAKIR, [3]SELIM GURGEN, [4]SEZAN ORAK, [5]OSMAN NURI CELIK, [6]MELIH CEMAL KUSHAN

[3]Anadolu University, Vocational School of Transportation, Eskisehir, Turkey
[1,2,4,5,6]Eskisehir Osmangazi University, Department of Mechanical Engineering, Bati Meselik, Eskisehir, Turkey E-mail: [1]asofuoglu@ogu.edu.tr, [2]fcakir@ogu.edu.tr, [3]selimgurgen@anadolu.edu.tr



**Abstract**—In this paper, an optimization approach was proposed to prevent chatter vibrations in turning operations. Chatter vibrations cause undesired surface finishing on the workpiece and should be avoided in machining operations. In this study, three models were developed. In the first model, the purpose is to predict and maximize stable cutting depths, whereas in the second model, the purpose is to predict chatter frequency. In the end, Analytic Network Process (ANP) was proposed to determine the optimum cutting, geometrical and modal parameters using two objectives because the response parameter, cutting depth affects surface roughness. Optimum cutting, geometrical and modal parameters were obtained without chatter vibrations. The models are developed to help operators and engineers in the different cutting environment to solve chatter vibration problem.



**Index Terms—**ANP, Chatter vibrations, Optimization, Regression models.


## I. INTRODUCTION

In spite of various efforts at optimization, the choice of optimal cutting conditions for turning operations is generally controlled by operators. The operators have experience and handbooks to control sufficient cutting parameters [1]-[2]. Generally, cutting conditions are chosen in a perceptive way or with handbooks help to programming cutting parameters to avoid vibration and process problems. In this sense, automation strategies are being presented in manufacturing environments to obtain more appropriate solutions [3]. Expert systems have been used primarily in the literature to prevent chatter vibrations. Morgan et al.'s [4] study provides an expert system which tries to solve the source of milling problems by using dynamics data. The expert system uses a fuzzy logic process to evaluate the signals and information, and suggests probable modifications to the process to accomplish milling processes. Rubio and Sen's [5] study presents the choice of tools in milling operations. An expert system based on numerical methods has been developed. The knowledge base is given by constraints in process variables, which let the user define the permitted cutting parameter interval. The tool cost model is developed and it is used to choose the proper cutting tool. When the cutting tool is chosen, the cutting parameters are computed. Rubio et al.'s [6] research provides an open and modular expert rule-based system to choose cutting parameters in milling. A cost function has been developed to Pareto-optimize cutting parameters subjected to tool-life, surface roughness, material removal rate and stability rate parameter purposes. This method is perceptive and it provides the possibility to interact with workers. In the end, the expert system is developed in modular form making it possible for incorporating new functionalities. Overall, in many cases, the detection of the vibrations is not clear. Additionally, operators are not guided to select the optimal cutting parameters during turning operations. There have been little optimization studies about cutting, geometrical and modal parameters during turning operations to prevent chatter.

This research attempts to determine the optimum cutting conditions without chatter. This paper has four parts. First, it reviews the extant literature relevant to expert systems about chatter prevention. Then, the methods used in the study are explained. Subsequently, the numerical results are presented. Regression models have been proposed to address the problem of chatter vibrations in turning operations. The paper concludes with a discussion of the theoretical and practical applications and directions for further research.

## II. METHODS

### *A. ANP Method*

ANP approach was developed by Saaty [7] in 1975. It is an extension of analytic hierarchy process (AHP). In fact, the elements in the hierarchy are usually interdependent. Low-level elements also control high-level elements. In some cases, there is a feedback relation between these elements. In this situation, the structure looks like a network. ANP approach was proposed to prevent these problems [8]. ANP system is separated into two parts: Control and Network Hierarchy.

### *B. Multiple Linear Regression Model*

The multiple linear regression formula results in a straight line, which minimizes the squared differences between the estimated and the actual output values. This is a very well-known statistical approach for making estimations [9]. The multiple linear equations are presented in (1, 2).

$$y_i = B_O + \sum_{i=1}^{n} B_i X_i + e_i \quad (1)$$

$$e_i = Yi_{actual} - Yi_{predicted} \quad (2)$$

$B_0$, Bi: Constant terms.
$Y_i$: The dependent variable.
$X_i$: The independent variables.
$e_i$: The error term (Normally distributed, mean 0, standard deviation σ ).
The coefficient of determination is calculated as follows (3).

$$R^2 = 1 - \frac{SSerror}{SStotal} \quad (3)$$

SS error: Sum of squares for errors.
SS total: Sum of squares for total.

## III. NUMERICAL STUDY

In the numerical study, experimental results are taken from Turkes [10], Sofuoglu [11, 12] and Gokmen's studies [13]. Detailed description of the experiments is given in these studies [10, 12]. Stable cutting depth and chatter frequency are dependent variables, whereas different workpiece and insert materials, geometries, cutting and modal parameters are independent variables. Data (192 points) were taken into consideration. Data has been divided into 122 training experiments and 70 test experiments randomly for stable cutting depth, whereas 96 training experiments and 55 test experiments were chosen randomly for chatter frequency [10, 12]. Regression models were developed and optimization study was conducted in the training stage, whereas in the test stage, $R^2$ (determination coefficients) values are calculated for each model.

### *A. Multiple Linear Regression Model for Stable Cutting Depth*

Multiple linear regression model was developed to maximize stable cutting depth. Table I shows the summary of coefficients and statistics for the model of stable cutting depth. Based on p values, coefficients are consistent at 5% significance level except two coefficients: stiffness ratio (k) and tool cross section. Half of the coefficients are consistent so consistency of coefficients test yielded positive results. Table II provides model summary for the model of stable cutting depths. Determination coefficient ($R^2$) and adjusted $R^2$ are computed 90.5% and 89.35% respectively. From this result, it can be seen that data fit the developed model well.

**Table I. Coefficients table for multiple linear model of stable cutting depth**

Coefficients

| Term | Coef | SE Coef | T-Value | P-Value |
|---|---|---|---|---|
| Constant | 19.96 | 2.70 | 7.40 | 0.000 |
| Workpiece diameter | 0.0425 | 0.015 | 2.89 | 0.005 |
| Workpiece length | -0.025 | 0.004 | -5.97 | 0.000 |
| Tool overhang length | -0.035 | 0.007 | -4.90 | 0.000 |
| Stiffness ratio (k) | 0 | 0 | 0.94 | 0.348 |
| Damping ratio (s) | 10.06 | 2.59 | 3.88 | 0.000 |
| Tool cross section | 0.0005 | 0.001 | 0.52 | 0.602 |
| Tool length | 0.073 | 0.018 | 4.10 | 0.000 |
| Approach angle | -0.116 | 0.025 | -4.59 | 0.000 |
| End clearance angle | -0.285 | 0.109 | -2.61 | 0.010 |
| Back rake angle | -0.220 | 0.105 | -2.10 | 0.039 |
| Side rake angle | 0.359 | 0.0941 | 3.82 | 0.000 |
| Workpiece hardness | -0.0265 | 0.0021 | -12.83 | 0.000 |
| The number of revolutions | -0.005 | 0.0003 | -17.86 | 0.000 |

**Table II. Model summary for multiple linear model of stable cutting depth**

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.585608 | 90.50% | 89.35% | 87.85% |

Table III presents the optimal parameters of stable cutting depth model. Response variable is stable cutting depth which is set 10 mm target value.

**Table III. The values of optimum parameters for multiple linear model of stable cutting depth**

Multiple Response Prediction

| Variable | Setting | Lower bound | Upper bound |
|---|---|---|---|
| Workpiece diameter | 100 | 40 | 100 |
| Workpiece length | 300 | 100 | 300 |
| Tool overhang length | 70 | 70 | 110 |
| k | 22800000 | 4.46e5 | 2.28e7 |
| s | 0.098 | 0.014 | 0.098 |
| Tool cross section | 400 | 400 | 625 |
| Tool length | 110 | 110 | 150 |
| Approach angle | 72.075 | 72 | 100 |
| End clearance angle | 3 | 3 | 7 |
| Back rake angle | -5 | -5 | 0 |
| Side rake angle | -6.887 | -7 | 0 |
| Workpiece hardness | 105 | 105 | 450 |
| The number of rev. | 90 | 90 | 710 |

In the test stage, the results are presented in Fig. 1. $R^2$ and adjusted $R^2$ are calculated 86.4% and 86.2% respectively. The determination coefficients decrease slightly compared to the training determination coefficients.

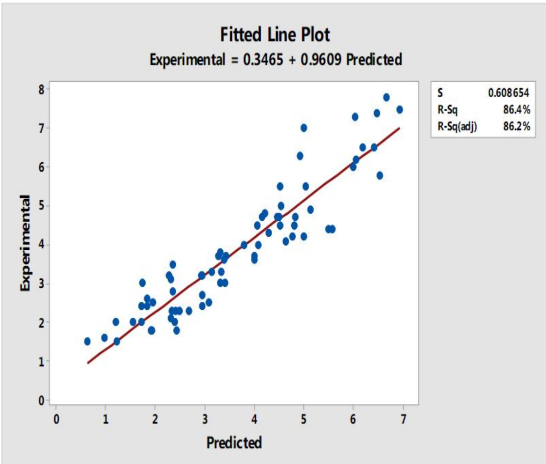


**Figure 1. Experimental and predicted stable cutting depths (mm)**

### *B. Multiple Linear Regression Model for Chatter Frequency*

Multiple linear regression model was developed to predict chatter frequency. Model coefficients and the statistics are summarized in Table IV. Coefficients of tool overhang length, k, s tool cross section and length are consistent at 5% significance level, whereas workpiece diameter and length, approach angle, workpiece hardness, the number of revolutions and cutting depths are not consistent at the same significance level.

**Table IV. Coefficients table for multiple linear model of chatter frequency**

Coefficients

| Term | Coef | SE Coef | T-Value | P-Value |
|---|---|---|---|---|
| Constant | 309 | 676 | 0.46 | 0.649 |
| Workpiece diameter | 0.34 | 2.46 | 0.14 | 0.889 |
| Workpiece length | -0.278 | 0.846 | -0.33 | 0.743 |
| Tool overhang length | -12.95 | 1.44 | -9.02 | 0.000 |
| k | 1.7e-5 | 3e-6 | 5.57 | 0.000 |
| s | 1711 | 525 | 3.26 | 0.002 |
| Tool cross section | -0.984 | 0.164 | -5.99 | 0.000 |
| Tool length | 12.99 | 5.18 | 2.51 | 0.014 |
| Approach angle | 7.70 | 8.37 | 0.92 | 0.360 |
| Workpiece hardness | -0.515 | 0.592 | -0.87 | 0.387 |
| The number of revolutions | -0.040 | 0.108 | -0.37 | 0.712 |
| Cutting depth | -8.0 | 19.8 | -0.40 | 0.688 |

Model summary for chatter frequency is set out in Table V. $R^2$ and adjusted $R^2$ is calculated 91.38% and 90.25% respectively. The equation fits the data well.

**Table V. Model summary for multiple linear model of chatter frequency**

Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 91.4974 | 91.38% | 90.25% | 88.51% |

In the test stage, the results are presented in Fig. 2. $R^2$ and adjusted $R^2$ are calculated 76.1% and 75.7% respectively. The determination coefficients decrease seriously compared to the training determination coefficients.

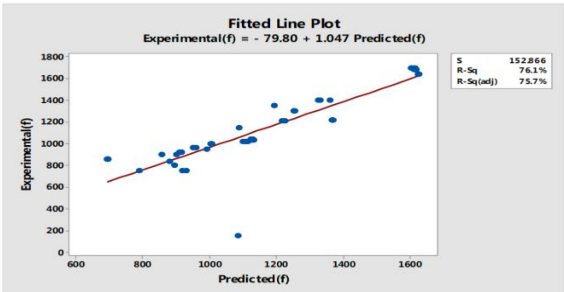


**Figure 2. Experimental and predicted chatter frequencies (Hz.)**

*C. Proposed ANP Model with Two Criteria*

ANP model has been proposed and it is shown in Fig. 3. Two criteria were chosen in ANP model: Stable cutting depth and surface roughness. For multipurpose problems with dependent variables, ANP is suitable model. In this problem, stable cutting depth affects surface roughness so ANP model is compatible for this problem. Experiments are handled as alternatives.

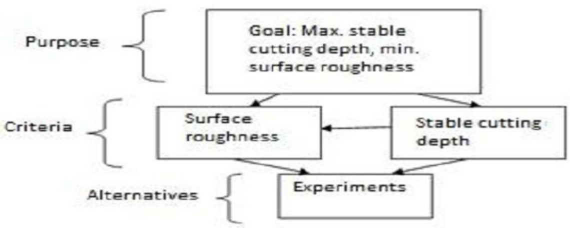


**Figure 3. Proposed ANP model structure**

## CONCLUSION

This study set out to determine the optimum cutting condition without chatter. Two different models have been developed and multiobjective model (ANP) has been proposed. It is clear that ANP model represents the chatter problem properly compared to the other models. The findings of this research provide insights for the optimization of cutting conditions during turning without chatter vibrations. Further research might explore the optimization of the cutting conditions during different process (milling, drilling etc.) without chatter. Additionally, ANP model might be developed with experimental data. This study helps operators and engineers make decisions to prevent chatter vibrations.

## REFERENCES

[1] P. Balakrishana, M.F. DeVries, “A review of computerized machinability database systems”, Proceedings of the NAMRC-X, pp. 348–356, 1982.

[2] [2] S.Y. Liang, R.L. Hecker and R. G. Landers, “Machining process monitoring and control: The state of the art” ASME Journal of Manufacturing Science andEngineering, 126 (2), pp. 297–310, 2004

[3] [3] Y. Koren, “ Adaptive control systems for machining”. American Society of Mechanical Engineers, Manufacturing Review, 2(1), pp. 6–15, 1989.

[4] [4] G. Morgan, R. Cheng, Y. Altıntas, K. Ridgway, “An expert troubleshooting system for the milling process” International Journal of Machine Tools and Manufacture, vol. 47, pp. 1417-1425, 2007

[5] [5] L. Rubio, M. Sen, “An expert mill cutter and cutting parameters selection system incorporating a control strategy” Proceedings of the 17th IFAC World Congress, 2008. International Federation of Automatic Control IFAC, COEX.

[6] [6] L. Rubio, M. Sen, A. Longstaff, S. Fletcher, “Model-based expert system to automatically adapt milling forces in Pareto optimal multi-objective working points”, Expert Systems with Application, vol. 40, pp.2312-2322, 2013.

[7] [7] T. L. Saaty, “Decision making with dependence and feedback: the analytic network process”. RWS Publications, 1996.

[8] [8] L. F. Wang, “The theory and algorithm of ANP. System Engineering Theories and Practices”, vol. 3, pp.44–50, 2001

[9] [9] SPSS Clementine Client 11.1, Help Topics, 2007.

[10] [10] E. Turkes, “Theoretical and experimental analysis of process damping in machine tool chatter vibration”, Ph.D. Thesis, University of Osmangazi, Eskisehir, Turkey, 2007.

[11] [11]M.A.Sofuoglu, “Experimental and Numerical Investigation of Chatter Stability Limits and Chatter Frequency in Turning Operations”, Master thesis, University of Osmangazi, Eskisehir, Turkey, 2015, [Unpublished]

[12] [12] M.A. Sofuoglu, Sezan Orak, “Predicting stable cutting depths in turning operations: an experimental and soft computing approach”, Applied Soft Computing Journal, 2015, [Submitted]

[13] [13] F. Gokmen, “Investigation the effect of insert material on chatter vibration in turning operations”, Master thesis, University of Osmangazi, Eskisehir, Turkey, 2015, [Unpublished]

★★★