VOL. 9, NO. 4, APRIL 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EXPERIMENTAL INVESTIGATION OF QUALITY INTERACTIONS IN MATERIAL PROCESSING

C. Phaneendra Kiran[1], Shibu Clement[2] and H. Chelladurai[3]
[1]Birla Institute of Technology and Science, Pilani Hyderabad campus, Hyderabad, India
[2]Birla Institute of Technology & Science, Pilani K K Birla Goa campus, Goa, India
[3]Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, India
E-Mail: phaneendrakiran@yahoo.co.in

ABSTRACT

This paper presents a methodology for quantification and evaluation of quality interactions in material machining process. The quality of a surface after turning operation depends on the quality of CNC machine structural components and also on the interactions between them. In this paper a methodology for finding quality interactions between the structural components is presented. The full factorial experiments design (135 experiments) has been carried out for measuring the responses of accelerometer and strain gauge. This data is analyzed using the analysis of variance (ANOVA) and interaction plots. The interactions which are significant are quantified using the ANOVA results. The quantified interactions can be substituted in the quality permanent to find a quality index. The resultant quality index is useful to the customer in evaluating the overall quality of a material machining process for optimal cutting parameter combination.

Keywords: material processing, quality, interactions, quality index, factorial design, turning.

INTRODUCTION

In this decade, computer integrated manufacturing process, robot controlled machining process etc. have improved the quality of manufacturing. Now customer demands high quality products for the lowest possible price. To meet customers' such demands and to face global competition, modern industries are facing various challenges towards achieving high dimensional accuracy with mirror surface finish on the products. To achieve dimensional accuracy and surface roughness of turning process the knowledge about the geometry of the cutting tool and cutting parameters is must. The literature reveals that important factors affecting the surface quality of a turned surface include cutting geometry and parameters [1-5], different forces acting on the cutting tool [6], type of coolant used, tool wear [7-8] etc. In addition to these parameters the surface quality of a turned work piece also depends on the quality of the CNC machine used, sensors detecting the positional accuracy, temperature, tool vibration, concentricity of the work piece with the axis of CNC, accuracy of automatic tool changer (ATC), accuracy of controller in considering the tool compensation etc. Authors in the past have proposed quality modeling of a CNC system [9].

Graph theoretical modeling

The quality of the components produced on a CNC turning centre depends on the functional quality of the different subsystems. The quality of structural components of a CNC turning centre are identified and shown in Figure-1. This quality hierarchical tree of CNC turning centre has six subsystems [9].

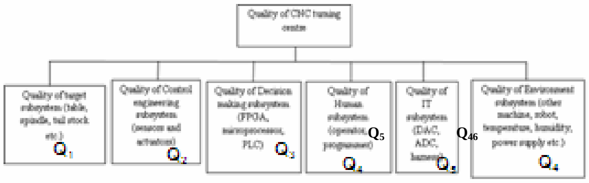

Figure-1. Quality hierarchical tree of CNC turning centre.

To translate the block diagram into a mathematical entity, a CNC quality digraph (*QD*) is developed and is shown Figure-2. In this digraph, each vertex is assigned to a subsystem and corresponding name can be referred from Figure-1. The interactions between the subsystems are represented by directed lines and are labeled according to the origin of interaction. For example, q_{12} represents that interaction is originating from Q_1 and terminating at Q_2. The *QD* is useful for visual inspection of the quality of subsystems and interactions. The visual analysis of quality interactions are as follows:

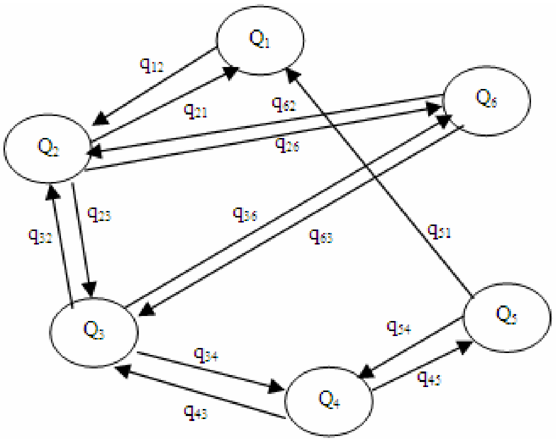

Figure-2. Quality digraph of CNC turning centre.

$\boldsymbol{q_{12}}$: Two accelerometers and a strain gauge mounted on the cutting tool collect information about the cutting tool condition. The quality of control engineering subsystem depends on the quality of the information interacted with the cutting tool.

$\boldsymbol{q_{21}}$: The accuracy in tool changing time of ATC (Automatic Tool Changer) depends on the accuracy of signals received by the control engineering subsystem.

$\boldsymbol{q_{23}}$ and $\boldsymbol{q_{32}}$: The quality of analog\digital input signal influence the quality of digital\analog output from the ADC\DAC.

$\boldsymbol{q_{26}}$: The quality of signal received by the other system like robot depends on the quality of information interaction with the control engineering subsystem.

$\boldsymbol{q_{62}}$: The functional quality of the control engineering subsystem depends on quality of the information about the environment subsystem (temperature, humidity etc.). Sometimes it may be the case that temperature at sensor location is less and at the other places it is higher.

$\boldsymbol{q_{34}}$: The quality of the decision made by the PLC, FPGA, or microprocessor depends on the quality of interfacing or interconnecting elements like bus or harness.

$\boldsymbol{q_{43}}$: The quality of signal received from the PLC, FPGA, or microprocessor depends on quality of the interconnecting elements transmitting the information.

$\boldsymbol{q_{36}}$: The quality of signal received by the environment (machine, robot etc.) depends on amount of signal loss (quality) in the data bus carrying the information.

$\boldsymbol{q_{63}}$: The performance quality of the interfacing connections depends on the surrounding temperature, humidity and the fluctuations in the power supply.

$\boldsymbol{q_{45}}$: The efficiency of the complex decision making subsystem depends on quality of the programmer interacting or programming it.

$\boldsymbol{q_{54}}$: The quality of the graphical user interface of the complex decision making subsystem depends upon skill of the operator using it.

$\boldsymbol{q_{51}}$: The quality of physical system depends on quality of the operator doing offsetting and referencing operations.

VPQM of CNC turning center.

To enable the QD for computational friendly, it is translated into matrix form. A matrix, MPS variable permanent matrix (VPQM) is obtained and given below:

$$VPQM_{CNC turning center} = \begin{array}{c} \begin{array}{cccccc c} 1 & 2 & 3 & 4 & 5 & 6 & \text{vertices} \end{array} \\ \left[\begin{array}{cccccc} Q_1 & q_{12} & 0 & 0 & 0 & 0 \\ q_{21} & Q_2 & q_{23} & 0 & 0 & q_{26} \\ 0 & q_{32} & Q_3 & q_{34} & 0 & q_{36} \\ 0 & 0 & q_{43} & Q_4 & q_{45} & 0 \\ q_{51} & 0 & 0 & q_{54} & Q_5 & 0 \\ 0 & q_{62} & q_{63} & 0 & 0 & Q_6 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \quad (1)$$

In this matrix, the diagonal elements, Qi, i=1,2..,6 represents quality of CNC turning center subsystems and the off-diagonal elements qij represent quality interaction of ith subsystem with jth subsystem.

VPQF of CNC turning center

The Variable Permanent Quality Function (VPQF) is derived from VPQM and given below:

$$\begin{aligned} &VPQF_{CNC \text{ turning center}} = Per(VPQM_{CNC \text{ turning center}}) = \\ &Q_1Q_2Q_3Q_4Q_5Q_6 + [(q_{12}q_{21})Q_3Q_4Q_5Q_6 + (q_{23}q_{32})Q_1Q_4Q_5Q_6 + (q_{34}q_{43})Q_1Q_2Q_5Q_6 \\ &+(q_{26}q_{62})Q_1Q_3Q_4Q_5 + (q_{45}q_{54})Q_1Q_2Q_3Q_6 + (q_{36}q_{63})Q_1Q_2Q_4Q_5] \\ &+[(q_{23}q_{36}q_{62})Q_1Q_4Q_5 + (q_{26}q_{63}q_{32})Q_1Q_4Q_5] + [(q_{12}q_{21})(q_{34}q_{43})Q_5Q_6 \\ &+(q_{12}q_{21})(q_{45}q_{54})Q_3Q_6 + (q_{12}q_{21})(q_{36}q_{63})Q_4Q_5 + (q_{23}q_{32})(q_{45}q_{54})Q_1Q_6 \\ &+(q_{26}q_{62})(q_{34}q_{43})Q_1Q_5 + (q_{26}q_{62})(q_{45}q_{54})Q_1Q_3 + (q_{36}q_{63})(q_{45}q_{54})Q_1Q_2] \\ &+[\{(q_{23}q_{36}q_{62})(q_{45}q_{54})Q_1 + (q_{26}q_{63}q_{32})(q_{45}q_{54})Q_1\} + \{(q_{12}q_{23}q_{34}q_{45}q_{51})Q_6\}] \\ &+[\{(q_{12}q_{21})(q_{36}q_{63})(q_{45}q_{54})\} + \{(q_{12}q_{26}q_{63}q_{34}q_{45}q_{51})\}] \end{aligned} \quad (2)$$

The terms in the equation (2) are arranged into groups. In which second group is absent due to no self interactions. Some of the subgroups are absent due to missing interactions between the subsystems; for example q25, q24, q46 etc. In the presence of all the interactions between the subsystems VPQFCNC turning center is supposed to have 6! =720 terms, but due to absence of some of the interactions, it is having 21 terms only.

The VPQF is a single numerical index in calculating the quality of a CNC machine. This index is also unique representation of permanent matrix given in equation (1). The quality of a subsystem can be quantified using the regular methods like statistical quality methods. To quantify the interactions between the sub systems an experimental or analytical technique is required. In the following section an experimental technique is presented.

Experimental evaluation of quality interactions

The quality of CNC turning centre depends on the quality of the subsystems like target subsystem (spindle, headstock, motor, etc.), control engineering subsystem (accelerometer signal, strain gauge signal etc.) etc. and the interactions between these subsystems. To quantify the interactions, pertinent parameters input (cutting speed, feed rate, depth of cut and flank wear) corresponding to target subsystem and the responses received by the control engineering subsystem (accelerometer and strain gauge) are taken into consideration. To quantify the quality interactions between the structural components of CNC machine, the experimental data is taken from literature [10]. The experiments were conducted on EN-8 steel tool with DNMG 150608 insert and Seco tool holder on CNC turning center without cutting fluid. Three sensors, one accelerometer in cutting direction mounted on tool holder, another accelerometer in feed direction mounted on turret and strain gauge is mounted on cutting tool. The accelerometer data is taken to FFT analyzer and the voltage induced due to strain is measured using Wheatstone half bridge circuit using Lab view.

The experiments were conducted using 3^k full factorial design, where number of levels are low (-1), intermediate (0), and high (1). The independent variables taken in this study were cutting speed, feed rate, and depth of cut. The artificial flank wear is fourth independent variable kept at five different levels ranging from 0 to 0.5.

The responses for different sensors are shown in Table 1- 3.

Table-1. Factorial design input parameters and the dynamic response of accelerometer in cutting direction [10].

Experimental conditions				**Amplitude of acceleration, g for different levels of flank wear**				
Ex no.	***CS***	***FR***	***DOC***	**0.5 *FW***	**0.4 *FW***	**0.3 *FW***	**0.2 *FW***	**0.0 *FW***
1	500	500	5	0.233	0.158	0.0298	0.0091	0.0107
2	500	500	4	0.0528	0.0079	0.0131	0.0043	0.0026
3	500	500	3	0.0456	0.0196	0.0026	0.0009	0.002
4	500	300	5	0.0759	0.0298	0.0132	0.0113	0.007
5	500	300	4	0.0389	0.0079	0.005	0.0058	0.0012
6	500	300	3	0.0348	0.0035	0.0047	0.0023	0.0014
7	500	100	5	0.0492	0.0033	0.0019	0.0028	0.0061
8	500	100	4	0.031	0.0029	0.0019	0.002	0.0031
9	500	100	3	0.0238	0.0013	0.0003	0.0006	0.0005
10	350	500	5	0.275	0.233	0.105	0.0199	0.0111
11	350	500	4	0.2	0.02	0.0219	0.0053	0.0036
12	350	500	3	0.0316	0.0111	0.0038	0.003	0.0034
13	350	300	5	0.253	0.0456	0.0247	0.0128	0.0083
14	350	300	4	0.154	0.0187	0.009	0.0085	0.0061
15	350	300	3	0.0275	0.0052	0.0074	0.0043	0.0016
16	350	100	5	0.189	0.0348	0.0105	0.0066	0.0064
17	350	100	4	0.0691	0.0115	0.0097	0.0009	0.0039
18	350	100	3	0.0107	0.0008	0.0026	0.0011	0.0009
19	200	500	5	0.265	0.265	0.232	0.0345	0.0153
20	200	500	4	0.232	0.0585	0.0241	0.009	0.0095
21	200	500	3	0.176	0.0065	0.0092	0.0087	0.0052
22	200	300	5	0.241	0.0621	0.0261	0.0442	0.0132
23	200	300	4	0.163	0.0389	0.011	0.0098	0.0091
24	200	300	3	0.158	0.0076	0.0058	0.0045	0.0019
25	200	100	5	0.106	0.0613	0.0145	0.0129	0.0112
26	200	100	4	0.0613	0.0186	0.0098	0.0092	0.0053
27	200	100	3	0.0186	0.0042	0.0077	0.0051	0.0037

Table-2. Factorial design input parameters and the dynamic response of accelerometer in feed direction [10].

Experimental conditions				**Amplitude of acceleration, g for different levels of flank wear**				
Ex no	***CS***	***FR***	***DOC***	**0.5 *FW***	**0.4 *FW***	**0.3 *FW***	**0.2 *FW***	**0.0 *FW***
1	500	500	5	0.267	0.245	0.0103	0.0089	0.0068
2	500	500	4	0.237	0.0883	0.0065	0.0058	0.0037
3	500	500	3	0.157	0.0277	0.0035	0.0025	0.0017
4	500	300	5	0.0939	0.0638	0.0071	0.0061	0.004
5	500	300	4	0.0448	0.0191	0.0049	0.0051	0.0031
6	500	300	3	0.0239	0.0087	0.0024	0.0017	0.0025
7	500	100	5	0.0457	0.0229	0.004	0.0033	0.0033
8	500	100	4	0.0408	0.0059	0.0028	0.0028	0.0024
9	500	100	3	0.0191	0.0065	0.0015	0.0007	0.0019
10	350	500	5	0.248	0.237	0.021	0.0136	0.0077
11	350	500	4	0.245	0.0389	0.0086	0.0061	0.0054
12	350	500	3	0.164	0.011	0.0054	0.0033	0.0044
13	350	300	5	0.249	0.0627	0.01	0.007	0.0054
14	350	300	4	0.19	0.0122	0.0066	0.0058	0.0034
15	350	300	3	0.143	0.0057	0.0033	0.0021	0.0027
16	350	100	5	0.0929	0.0264	0.005	0.0053	0.0037
17	350	100	4	0.0264	0.0055	0.0036	0.0029	0.0028
18	350	100	3	0.0249	0.0045	0.0031	0.0007	0.0025
19	200	500	5	0.271	0.121	0.0226	0.0194	0.0083
20	200	500	4	0.264	0.0239	0.0123	0.0094	0.0067
21	200	500	3	0.169	0.0017	0.0085	0.0037	0.0051
22	200	300	5	0.233	0.0408	0.0159	0.0125	0.0061
23	200	300	4	0.147	0.0063	0.012	0.0084	0.0041
24	200	300	3	0.131	0.0039	0.0062	0.0045	0.0034
25	200	100	5	0.192	0.0167	0.0127	0.0064	0.0049
26	200	100	4	0.133	0.0249	0.0089	0.0033	0.0032
27	200	100	3	0.0601	0.0044	0.0081	0.001	0.0028

Table-3. Factorial design input parameters and the dynamic response of Strain Gauge Bridge [10].

Experimental conditions				**Amplitude of acceleration, g for different levels of flank wear**				
Ex no	***CS***	***FR***	***DOC***	**0.5 *FW***	**0.4 *FW***	**0.3 *FW***	**0.2 *FW***	**0.0 *FW***
1	500	500	5	0.267	0.245	0.0103	0.0089	0.0068
2	500	500	4	0.237	0.0883	0.0065	0.0058	0.0037
3	500	500	3	0.157	0.0277	0.0035	0.0025	0.0017
4	500	300	5	0.0939	0.0638	0.0071	0.0061	0.004
5	500	300	4	0.0448	0.0191	0.0049	0.0051	0.0031
6	500	300	3	0.0239	0.0087	0.0024	0.0017	0.0025
7	500	100	5	0.0457	0.0229	0.004	0.0033	0.0033
8	500	100	4	0.0408	0.0059	0.0028	0.0028	0.0024
9	500	100	3	0.0191	0.0065	0.0015	0.0007	0.0019
10	350	500	5	0.248	0.237	0.021	0.0136	0.0077
11	350	500	4	0.245	0.0389	0.0086	0.0061	0.0054
12	350	500	3	0.164	0.011	0.0054	0.0033	0.0044
13	350	300	5	0.249	0.0627	0.01	0.007	0.0054
14	350	300	4	0.19	0.0122	0.0066	0.0058	0.0034
15	350	300	3	0.143	0.0057	0.0033	0.0021	0.0027
16	350	100	5	0.0929	0.0264	0.005	0.0053	0.0037
17	350	100	4	0.0264	0.0055	0.0036	0.0029	0.0028
18	350	100	3	0.0249	0.0045	0.0031	0.0007	0.0025
19	200	500	5	0.271	0.121	0.0226	0.0194	0.0083
20	200	500	4	0.264	0.0239	0.0123	0.0094	0.0067
21	200	500	3	0.169	0.0017	0.0085	0.0037	0.0051
22	200	300	5	0.233	0.0408	0.0159	0.0125	0.0061
23	200	300	4	0.147	0.0063	0.012	0.0084	0.0041
24	200	300	3	0.131	0.0039	0.0062	0.0045	0.0034
25	200	100	5	0.192	0.0167	0.0127	0.0064	0.0049
26	200	100	4	0.133	0.0249	0.0089	0.0033	0.0032
27	200	100	3	0.0601	0.0044	0.0081	0.001	0.0028

For these responses, the analysis of variance (ANOVA) is done at 95% confidence intervals and the analysis is given in the Tables 4 to 6. In these tables the parameters having the values of $P \leq 0.05$ are significant and are marked with a '*' symbol. This analysis is conducted using a software, MINITAB 15.0 In Table-4 the P value of cutting speed (*CS*), feed rate (*FR*), depth of cut (*DOC*) and flank wear (*FW*) are significant. In addition to these the interactions between these independent parameters (Eg: *CS* and *DOC*) are also significant, which was not revealed previously [10].

Table-4. ANOVA for effect of machining parameters w.r.t. dynamic response of accelerometer in cutting direction.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CS	2	0.0264233	0.0264233	0.0132117	22.86	0.000*
FR	2	0.0476122	0.0476122	0.0238061	41.18	0.000*
DOC	2	0.0802331	0.0802331	0.0401166	69.40	0.000*
FW	4	0.2352414	0.2352414	0.0588103	101.74	0.000*
CS*FR	4	0.0054097	0.0054097	0.0013524	2.34	0.076
CS*DOC	4	0.0074328	0.0074328	0.0018582	3.21	0.025*
CS*FW	8	0.0248704	0.0248704	0.0031088	5.38	0.000*
FR*DOC	4	0.0292265	0.0292265	0.0073066	12.64	0.000*
FR*FW	8	0.0407017	0.0407017	0.0050877	8.80	0.000*
DOC*FW	8	0.0525433	0.0525433	0.0065679	11.36	0.000*
CS*FR*DOC	8	0.0009924	0.0009924	0.0001240	0.21	0.986
CS*FR*FW	16	0.0113624	0.0113624	0.0007102	1.23	0.300
CS*DOC*FW	16	0.0205464	0.0205464	0.0012841	2.22	0.027*
FR*DOC*FW	16	0.0275549	0.0275549	0.0017222	2.98	0.004*
Error	32	0.0184973	0.0184973	0.0005780		

Table-5. ANOVA for effect of machining parameters w.r.t. dynamic response of accelerometer in feed direction.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CS	2	0.0035165	0.0035165	0.0017582	14.22	0.000*
FR	2	0.0543179	0.0543179	0.0271589	219.69	0.000*
DOC	2	0.0333204	0.0333204	0.0166602	134.77	0.000*
FW	4	0.3913171	0.3913171	0.0978293	791.35	0.000*
CS*FR	4	0.0075929	0.0075929	0.0018982	15.35	0.000*
CS*DOC	4	0.0003271	0.0003271	0.0000818	0.66	0.623
CS*FW	8	0.0262597	0.0262597	0.0032825	26.55	0.000*
FR*DOC	4	0.0073883	0.0073883	0.0018471	14.94	0.000*
FR*FW	8	0.0827171	0.0827171	0.0103396	83.64	0.000*
DOC*FW	8	0.0390739	0.0390739	0.0048842	39.51	0.000*
CS*FR*DOC	8	0.0013672	0.0013672	0.0001709	1.38	0.242
CS*FR*FW	16	0.0205260	0.0205260	0.0012829	10.38	0.000*
CS*DOC*FW	16	0.0037037	0.0037037	0.0002315	1.87	0.064
FR*DOC*FW	16	0.0242301	0.0242301	0.0015144	12.25	0.000*
Error	32	0.0039559	0.0039559	0.0001236		

Table-6. ANOVA for effect of machining parameters w.r.t. dynamic response of Strain Gauge Bridge.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CS	2	25.297	25.297	12.648	10.53	0.000*
FR	2	95.811	95.811	47.905	39.88	0.000*
DOC	2	91.280	91.280	45.640	38.00	0.000*
FW	4	57.305	57.305	14.326	11.93	0.000*
CS*FR	4	36.437	36.437	9.109	7.58	0.000*
CS*DOC	4	21.454	21.454	5.363	4.47	0.006*
CS*FW	8	20.081	20.081	2.510	2.09	0.067
FR*DOC	4	123.492	123.492	30.873	25.70	0.000*
FR*FW	8	74.850	74.850	9.356	7.79	0.000*
DOC*FW	8	82.925	82.925	10.366	8.63	0.000*
CS*FR*DOC	8	29.086	29.086	3.636	3.03	0.012*
CS*FR*FW	16	35.730	35.730	2.233	1.86	0.066
CS*DOC*FW	16	21.162	21.162	1.323	1.10	0.394
FR*DOC*FW	16	109.099	109.099	6.819	5.68	0.000*
Error	32	38.435	38.435	1.201		

To analyze the interactions between these parameters, the interactions plots for all the three sensor responses are plotted as shown in the Figures 3 to 4. In Figure-3 the interaction plot for the accelerometer (cutting direction) is plotted with respect to different parameters *CS*, *FR*, *DOC* and *FW*. This figure shows that the amplitude of vibration increases with feed rate which results in increased dynamic force. With increased dynamic force, the stiffness of the tool will decrease. In each box, the lines representing the parameters at different levels are intersecting with each other. It shows that the response of accelerometer is varying when both the parameters varied simultaneously. Hence, there exist interaction between those parameters, and needs attention during design of subsystems.

In Figure-4, the response of accelerometer (feed direction) is plotted with respect to the combination of parameters *FR*, *CS*, *DOC* and *FW*. In this analysis, it is observed that the maximum amplitude of the acceleration in noticed for the combination of high *FW*, low *CS*, high *FR*, and high depth of cut. In Figure-5, the increase in micro strain is low up to intermediate level of the parameters *FR*, *DOC* and it is high up to intermediate levels of *CS* and is low at the high speeds. The increase in strain is moderate up to 0.2 *FW* and is high for the higher *FW*. The increase in strain rate is due to increase in the dynamic force.

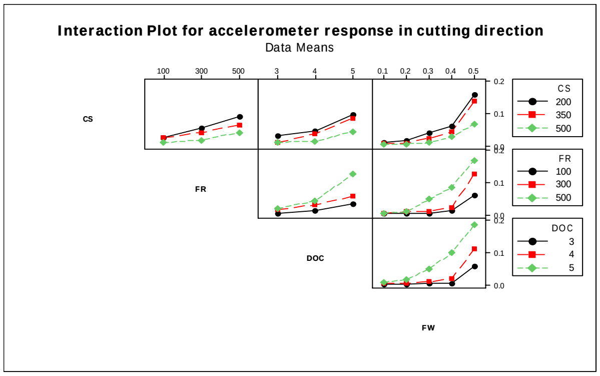

Figure-3. Interaction plot of machining parameters for the response of accelerometer mounted in cutting direction.

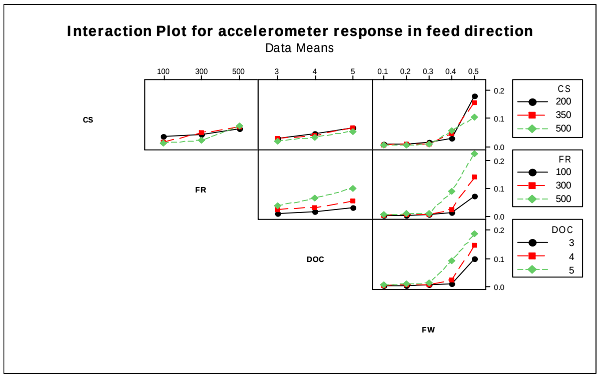

Figure-4. Interaction plot of machining parameters for the response of accelerometer mounted in feed direction.

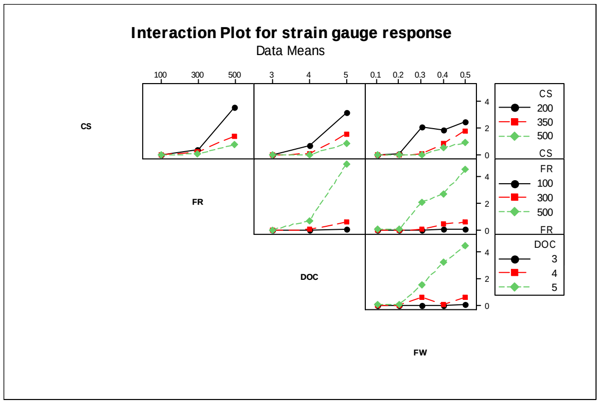

Figure-5. Interaction plot of machining parameters for the response of Strain Gauge Bridge.

The quantification of this interaction effect is significant in the current study. The interaction effect can be quantified as follows:

$$\text{Interaction effect}=\frac{1}{2}\left[\begin{array}{l}\text{effect of one factor at high level of the other factor-}\\ \text{effect of the same factor at low level of the other factor}\end{array}\right]$$

For example, FR and DOC are the two factors, each kept at three levels. The interaction effect (FR x DOC) for the response the amplitude of vibration in cutting direction is given by:

$$\text{FR x DOC}=\frac{1}{2}\left[\text{effect of FR at high level of DOC-effect of FR at low level of DOC}\right]$$

From the experimental data and from the Figure-1, the parameters FR and *DOC* interaction effect is significant when the *CS* and *FW* are at their minimum (200 and 0 respectively). Hence, the interaction effect for the *FR* and *DOC* for the signal amplitude of vibration in cutting direction can be calculated using Table-7.

Table-7. Values of *FR* and *DOC* for calculating interaction effect.

FR	***DOC***	**Accelerometer response**
500	5	0.0153
500	3	0.0052
100	5	0.0112
100	3	0.0037

$$\text{FR x DOC}=\frac{1}{2}\left[(0.0153\text{-}0.0112)\text{-}(0.0052\text{-}0.0037)\right]=0.0013$$

This interaction is nothing but q_{12} shown in Figure-2. In the same way other interaction effects can be calculated for different sensor responses.

Quality index (*QI*)

The *QI* of CNC turning centre would be obtained by substituting the values of Q_i's and q_{ij}'s into the equation (1). In this case quality of Q_i's and q_{ij}'s were classified into quantifiable (measurable) factors and unquantifiable factors in the following manner. The quantifiable (measurable) quality factors were divided into five ranges and each range was assigned a value. For example, the quality of the complex decision making subsystem (Q_4) depends on how fast the feedback loop is updated. For a 1-2 axes CNC machines the feedback loop update time ranges from 31µsec to 62µsec. The assignment of values to this quantity is shown in the Table-8. In this case, the lower the feedback time, the better the performance. In some cases, the higher the quality factor, the better the performance.

The unquantifiable quality factors like operator skill, a relative quantity, are important in evaluating the quality interaction q_{54}. In this case, the opinion of the experts was taken and the quality interaction was divided into a range (Table-9). For this unquantifiable interaction (q54), the operator with the greatest skill was assigned the highest numerical value, 5, in 1-5 scale and the operator with the lowest skill was assigned the lowest value, 1 in the scale. The interactions like q12 were calculated based on the experiments and e normalized in the scale (1-5).

Table-8. Values range for quantifiable quality factors.

Feedback loop update time	Value assigned
31 µsec-37.2 µsec	5
37.3 µsec-43.4 µsec	4
43.5 µsec-49.6 µsec	3
49.7 µsec-55.8 µsec	2
55.9 µsec-62 µsec	1

Table-9. Values range for unquantifiable quality factors.

Operator skill	Value assigned
Very high	5
High	4
Moderate	3
Less	2
Very less	1

Similarly the rest of the quality factors were quantified. The range of values or the scale (1-5) was maintained uniform for all the quality factors. For the purpose of illustration, numerical values within the range of scale were assigned and the values were tabulated (Table-9).

Table-10. Numerical quality values of a CNC turning center.

Subsystem interaction	Q_1, Q_2, Q_3, Q_4, Q_5, Q_6	q_{12}, q_{21}	q_{23}, q_{32}	q_{26},q_{62}	q_{34},q_{43}	q_{36},q_{63}	q_{45}, q_{54}	q_{51}
Quantity (1-5)	5, 4, 3, 4, 5, 3	3, 2	4, 5	3, 4	5, 4	2, 4	2, 3	4

The respective numerical values for all the subsystems and the quality interactions from the Table-10 were substituted in equations (1) and (2) and the quality index (QI) obtained for a CNC turning center was as follows:

$$VPQM_{CNCturningcenter} = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array}\ \text{vertices} \\ \left[\begin{array}{cccccc} 5 & 3 & 0 & 0 & 0 & 0 \\ 2 & 4 & 4 & 0 & 0 & 3 \\ 0 & 5 & 3 & 5 & 0 & 2 \\ 0 & 0 & 4 & 4 & 2 & 0 \\ 4 & 0 & 0 & 3 & 5 & 0 \\ 0 & 4 & 4 & 0 & 0 & 3 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \qquad (3)$$

$QI_{\text{CNC turning center}} = 52612$

For interpreting this index, industry should set its bench mark positive and negative indices by substituting the maximum and minimum possible quality. In this case, the positive benchmark or maximum possible QI and negative benchmark or minimum possible QI were

$$\left(VPQM_{CNCturningcenter}\right)_{MAX} = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array}\ \text{vertices} \\ \left[\begin{array}{cccccc} 5 & 5 & 0 & 0 & 0 & 0 \\ 5 & 5 & 5 & 0 & 0 & 5 \\ 0 & 5 & 5 & 5 & 0 & 5 \\ 0 & 0 & 5 & 5 & 5 & 0 \\ 5 & 0 & 0 & 5 & 5 & 0 \\ 0 & 5 & 5 & 0 & 0 & 5 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \qquad (4)$$

$(QI_{\text{CNC turning center}})_{MAX} = 3, 28, 125$

$$\left(VPQM_{CNCturningcenter}\right)_{MIN} = \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array}\ \text{vertices} \\ \left[\begin{array}{cccccc} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \end{array} \qquad (5)$$

(QICNC turning center)MIN = 21

Hence, the QI of the CNC lathe with similar structure varies between 21 to 3, 28, 125. Using these benchmark indices the areas of quality improvement can be identified and corrective action can be taken. For example, if the value of the quality interaction q_{54} is improved from the existing value of 3 to 5, then the percentage change in QI as compared to the original is 10.5%. This shows that a lot of corrective actions can be taken to improve the quality of a CNC machine based on the QI. The interaction q54 is between CNC interface and the operator. The existing control panel for the GILDMEISTER CTX 400 Serie2 lathe is shown in Figure-6. The design variables available are letter size, button size, button color, letter color, background color, button shape, touch panel operations label, and number of buttons. When the control panel is designed for 3-factorial experiments for the eight design variables, it gives 18 experimental arrangements. A customer preference is needed for the preference metric. One way to do this is to show the panels to the customers and have them rank order the control panels in terms of how well they like them. This ranks each trial into a numbering scheme from 1 to 18, best to worst. This can be replicated with many customers, and so a replicated set of data may be developed and ANOVA on the data could be applied to analyze the data.

Using this method the best control panel could be chosen for a given application and the quality of the interaction would be improved. It is quite logical that a CNC turning centre with high quality subsystems and high quality interactions will have high overall quality. This index is useful to the industry in evaluating the quality of a CNC machine in the design phase, pre-procurement phase, and in commissioning after the procurement. The methodology is demonstrated up to subsystem level only. It is recommended that one should apply this methodology up to component level.

Figure-6. Control panel of GILDMEISTER CTX 400 Serie2 lathe.

CONCLUSIONS

In this paper, a systems based approach for quality modeling of a CNC machine was presented. A graph theory, matrix algebra and permanent based mathematical model was developed. The developed quality digraph is useful for visual inspection of a CNC machine, the developed matrices are useful for higher computational purpose, and the permanent is the unique way of representing structural quality in the form of a multinomial. An experimental method was presented for quantification of quality interactions between the subsystems.

The proposed methodology was applied by substituting the numerical values. From the experiments conducted, the interaction between feed rate and depth of cut was obtained and the value was 0.0013. The quality of the subsystems and their interactions were obtained in the scale of 1 to 5. After substituting the values, the obtained quality index for this CNC (GILDMEISTER CTX 400 Serie2) was 52,612. To compare the quality index of the CNC lathe the positive and negative benchmark quality indices were obtained - 3, 28, 125 and 21. Using this methodology the areas of improvement for the quality can be identified and improved. For example, if you improve the interaction value of q_{54} from 3 to 5 then the quality index improves by 10.50% as compared to the original. The methods for quality improvement are suggested.

The designer may use this methodology during the conceptual stage for quality based evaluation and optimal selection of a CNC machine from a set of alternatives. The manufacturer may choose the optimal manufacturing process based on the desirable quality derived using this methodology. The maintenance engineer may monitor the health of a CNC machine and can take a corrective action based on the real-time *QI* of a CNC machine. The developed coefficient of similarity and dissimilarity would be helpful for comparison and ranking between available candidates. With the help of the proposed methodology, the intermediate specifications derived during the design phase can be verified for a quality index and the corrective action may be taken for improving the quality. The proposed methodology is highly flexible, comprehensive and gives a new direction to industry to achieve high quality CNC turning center.

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