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Spectral Coherence Analysis between Grinding Interaction Forces and the Relative Motion of the Workpiece and the Cutting Tool

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Abstract**—**Grinding operation is performed in order to obtain desired surfaces precisely in machining process. The needed relative motion between the cutting tool and the workpiece is generally created either by the movement of the cutting tool or by the movement of the workpiece or by the movement of both of them as in our case. For all these cases, the coherence level between the movements and the interaction forces is a key influential parameter for efficient grinding. Therefore, in this work, spectral coherence analysis has been performed to investigate the coherence level between grinding interaction forces and the movement of the workpiece on our robotic-grinding experimental setup in METU Mechatronics Laboratory.

Keywords**—**Coherence analysis, correlation, FFT, grinding, Hanning window, machining, Piezo actuator, reverse arrangements test, spectral analysis

I. Introduction

GRINDING operation is one of the most important processes in order to obtain qualified surfaces. However, the quality of the operation is mostly dependent on the skills of the operator. Therefore, automated or robotized grinding cells have gained recognition in the industry. The robotic-deburring experimental setup used in this work is shown in Figs. 1 and 2 [1]. In addition to 6-DoF parallel manipulator, the experimental setup has an additional 1 DoF actuated by piezo actuator. The actuator is fixed to the properly constrained table, presents a single DoF in the x direction as shown in Fig. 2. While performing grinding in y direction as shown in the same figure, the workpiece can be moved in x direction, therefore demanded surface form can be obtained.

In [2], a compliant motion control method was implemented into the robotic-deburring experimental setup. It was shown that the roughness of the surface can be improved without knowing the actual surface form. The case in which the surface profile of the workpiece is not known was investigated. In this work; the interaction force between the tool and the workpiece was tried to be kept constant. Admittance force control was performed using the position control of the piezo actuator. In the current work the causality, in other words coherence, between the position of the piezo (correspondingly the workpiece) and the interaction force between the workpiece and the cutting tool will be investigated by FFT based spectral coherence analysis.

Reverse arrangements test [3] is performed on the datasets in order to check the stationarity.

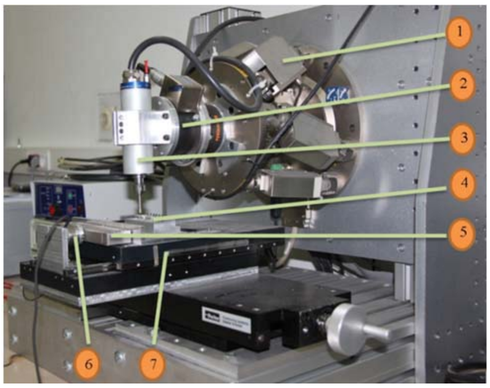

Fig. 1 The overall appearance of the test setup

The parts shown in Fig. 1 are:

1. Hexapod (6 DoF): It has 6 DoF and is used to move the spindle which carries the tool.
2. ATI Gamma IP60 Force / Torque Sensor
3. Spindle
4. Workpiece (St37)
5. Piezo Actuator
6. ATI Nano25 Force / Torque Sensor
7. Table (which has 1 DoF in x direction as shown in Fig. 2 during machining)

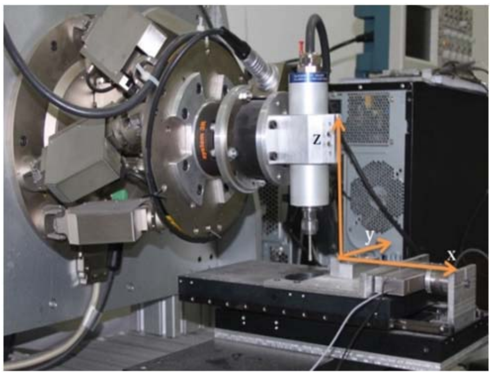

Fig. 2 The overall appearance of the test setup and coordinate axes

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Piezo Actuators are used in lots of applications in which sensitive positioning is needed. For instance, in [4], B. Denkena et al. developed a controller in order to perform grinding of a rotating crankshaft. Since the crankshaft is rotating, the grinding tool and/or the workpiece need to compensate the possible grinding errors caused by the rotation of the asymmetric crankshaft. Therefore, the needed compensation is performed by piezohydraulic hybrid positioning.

In [5] A. Rashid et al. present an active controlled palletized workpiece holding system for milling operations. The active control system developed here employs piezo-actuators to control the force dynamically.

The input for the piezo actuator in our setup (Figs. 1 and 2) is voltage (0 to 10 V) and the output is position (0 to 1 mm). While giving input, it is possible to obtain the actual position data of the piezo actuator by strain gauge sensors installed on it.

In grinding operations force/torque sensors are extensively used as well. These sensors are used to measure the amount of force applied on parts of the machine. Additionally, by measuring the force applied on the tool, they can be used to check whether the contact is performed between the tool and the workpiece or not. Also if the contact is performed, the force/torque sensors can be used to measure the level of the contact.

In [6], S. Lee et al. utilized force/torque sensors in order to develop an adaptive force control based deburring algorithm. This algorithm is used to maintain the interaction between the workpiece and the deburring tool. The algorithm aims to make the normal force and normal velocity equal to zero. Throughout this adaptive algorithm, big burrs can be efficiently removed and damage to the workpiece under unexpected conditions can be avoided.

In [7], J. Park et al. developed an algorithm in order to control the interaction force between tool and the workpiece. A plate and a roller were used to guide the tool. These guides prevent the tool to exceed a certain depth of cut and the interaction between the tool and the workpiece is kept applying a force constantly.

On our robotic-deburring experimental setup, there are two force/torque sensors. These sensors are able to measure the data of the forces on 3 Cartesian basis axes and of the torques about the same axes. In this work the one which is shown by 2 in Fig. 1 was used in order to measure the interaction forces in x and y direction. The transducer electronics have bandwidth of 5 kHz to 10 kHz (depending on gain settings).

The purpose of the current work is to investigate the coherence between the workpiece and the cutting tool.

In this paper, firstly the Simulink Model developed for the experiment is given in Section II and stationary tests on the collected data are given in Section III; then spectral density analysis is given in Section IV. Finally results and conclusions are given.

II. The Experiment

A sine input frequency of 1 Hz and amplitude of 0.5 Volts (which corresponds to $500\ \mu m$ movement of piezo) was given to piezo actuator as an input. While this sinusoidal motion was performed by the piezo actuator, the tool was moved in tangential direction by 6-DoF PI H-824. The grinding scenario is illustrated in Fig. 3.

The sampling time was 0.00125. The experiment time was approximately 70 seconds. A section of the grinding process measurements is shown in Fig. 4 as an example. The sample length, in other words; the ground distance is 15 mm; feedrate of the tool was selected as 0.2 mm/sec. A cylindrical CBN (Cubic boron nitride) cutting tool was used for the experiment and the workpiece material was st37.

As a result, 3 datasets are obtained. These datasets are:

- Position of the piezo
- Interaction force component in x direction
- Interaction force component in y direction

One of these datasets includes 55296 data.

An important step in obtaining the correct data from robotic-grinding experimental setup is data filtering. Therefore, digital filters are extensively used. MATLAB provides several filtering functions. However, after selecting an appropriate filter, the important issue to be solved becomes determining the optimal parameters of the desired filter. As shown in [8], inappropriate filters and parameters will result in incorrect data.

In this work, running average filters has been used at the interaction force datasets in both axis and the position dataset of the piezo actuator in order to decrease the noise.

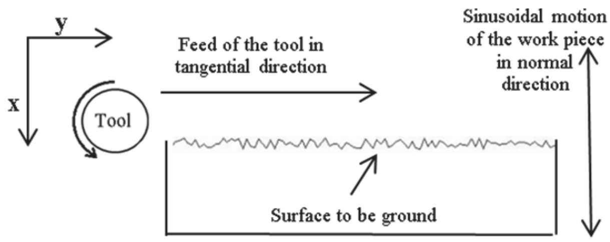

Fig. 3 Grinding Process

III. Stationary Tests

A non-parametric test, reverse arrangements test [3] was performed for stationarity analysis. The sampling time is 0,00125 as mentioned before. For mean square calculation, following equality is used:

$$E[\Psi_i^2] = \sigma_i^2 + \mu_i^2 \quad (1)$$

where; μ: Mean value of the i^{th} segment; σ: Standard deviation of the i^{th} segment.

The datasets each of which includes 55296 data are divided into 54 segments in order to increase the number of samples and after finding the spectral density estimates of the segments separately, the averages are taken, therefore random noise is decreased.

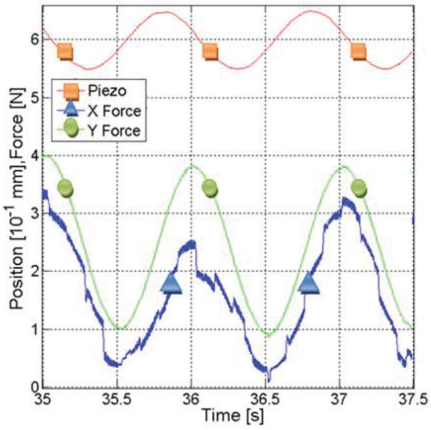

Fig. 4 "X Force" indicates the interaction force in X axis, "Y Force" indicates the interaction force in Y axis and "Piezo" indicates the actual position of the piezo actuator

Since the data which is processed in FFT algorithm is to be divided into 54 segments, the stationarity tests are performed to each segment separately. Moreover, each segment is divided into 16 segments again for performing stationary tests. As a result, each segment has 55296/54/16=64 data. For the sake of clarity, the detailed explanation of the stationarity analysis is given just for the first segment of the dataset of the position of the piezo actuator.

A. Dataset of Position of the Piezo Actuator

1) Preparation for the Test

Mean square values are plotted in Fig. 5.

2) Results

Level of significance is taken as 10%;

$$\alpha = 0.10 \quad \Rightarrow \quad \frac{\alpha}{2} = 0.05 \;\; \& \;\; 1 - \frac{\alpha}{2} = 0.95 \qquad (2)$$

For 16 Data Segments;

Reverse arrangements tests were performed on mean square values by comparing each element to elements after them and generating "A" value for number of reverse arrangements. In this case, number of reverse arrangement is:

$$A = 48 \qquad (3)$$

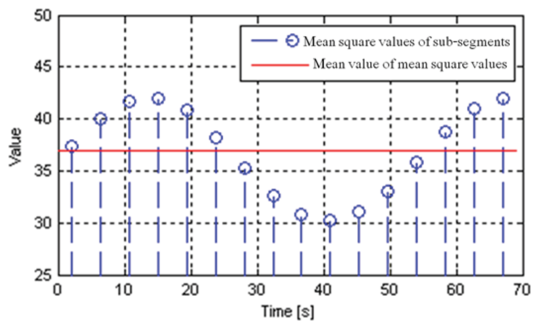

Fig. 5 Mean square values of 16 equal segments of the first segment

Data divided into $N = 16$ segments;

$$A_{N;1-\frac{\alpha}{2}} = 41 < \boldsymbol{A_{16}} = \mathbf{48} < A_{N;\frac{\alpha}{2}} = 78 \qquad (4)$$

(Inequality holds)

Hence number of the runs is inside the above range, it can be said that the dataset shows no trend and has stationary character according to reverse arrangements test in 10% level of significance.

Additionally, after performing stationary test to other segments, it was seen that all the data show no trend and has stationary character according to reverse arrangements test in 10% level of significance.

B. Force Data in X Direction

According to the procedure given in the previous section, stationarity analysis was performed. As a result, it can be said that the data except one segment shows no trend and has stationary character according to reverse arrangements test. 41 of the 54 segments were stationary according to 10% level of significance. 7 of the results were stationary according to 5% level of significance. 5 of the results were stationary according to 2% level of significance. However, only 1 segment out of 54 segments appeared to be out of the range. Analysis for this segment (Level of significance is taken as 2%);

$$\alpha = 0.02 \quad \Rightarrow \quad \frac{\alpha}{2} = 0.01 \quad \& \quad 1 - \frac{\alpha}{2} = 0.99 \qquad (5)$$

Data divided into $N = 16$ segments;

$$A_{N;1-\frac{\alpha}{2}} = 34 < \boldsymbol{A_{16}} = \mathbf{30} < A_{N;\frac{\alpha}{2}} = 85 \qquad (6)$$

(Inequality does **NOT** hold)

Since it is very close to the lower limit value which is 34, the dataset was assumed to be stationary.

C. Force Data in Y Direction

According to the procedure given in the previous section, stationarity analysis was performed. As a result, it can be said that all the data show no trend and have stationary character according to reverse arrangements test in 10% level of significance.

IV. Spectral Density Function Estimates

The number of data to be processed in FFT algorithm [9] should be power of 2. In our case, since the number of data in one segment is already equal to a power of 2 (2^{10}=1024), there is no reason for zero padding.

After performing spectral analysis, the averages of the spectral estimate values of the segments are taken. Therefore, as mentioned earlier, random noise is decreased.

Hanning window [3] is applied as a weighting function. Also zeroth order trend is removed from the datasets.

Sampling period:

$$h = 0{,}00125\ s \qquad (7)$$

Sampling frequency:

$$f_s = \frac{1}{h} = \frac{1}{0,00125\ s} \quad \Rightarrow \quad f_s = 800\ Hz \tag{8}$$

According to the Nyquist Sampling Theorem, maximum frequency of interest:

$$f_{max} = f_c = \frac{f_s}{2} = 400\ Hz \tag{9}$$

Number of sample records:

$$S = 54 \tag{10}$$

Number of data points in each sample:

$$N = 1024 \tag{11}$$

Record Length of 1 sample:

$$T = N * h = 1024 * 0,00125 = 1,28\ s \tag{12}$$

Having an accuracy figure of unity:

$$\frac{\sigma}{m} \cong 1 \tag{13}$$

Therefore, effective bandwidth becomes:

$$\frac{\sigma}{m} \cong \frac{1}{\sqrt{Be * T}} \rightarrow Be = \frac{1}{T} = \frac{1}{1,28} = 0,78\ Hz \tag{14}$$

Number of adjacent spectral estimates that should be averaged can be calculated as;

$$(2n + 1) = Be * T \ \Rightarrow \tag{15}$$

$$n = \frac{1}{2} * (0,78\ [Hz] * 1,28\ [s] - 1) = 0 \tag{16}$$

Therefore; $(2n + 1) = 1$ (17)

Adjacent spectral estimates must be averaged with equal weighting. Therefore, there will be no averaging.

Following relations were used for the analysis:

$$G_y = 2S_y \qquad G_x = 2S_x$$

$$G_{xy} = C_{xy} - jQ_{xy} \qquad 2S_{xy} = C_{xy} - jQ_{xy}$$

$$\gamma_{xy}^2 = \frac{|G_{xy}|^2}{G_x * G_y} \qquad \psi^2 = \int_{-\infty}^{+\infty} G(\omega) d\omega$$

$$S_{xx_k} = x_k^* x_k \qquad S_{xy_k} = x_k^* y_k$$

$$|G_{xy}| = \sqrt{C_{xy}^2 + Q_{xy}^2} \qquad \theta_{xy} = \tan^{-1}\left[\frac{Q_{xy}}{C_{xy}}\right]$$

where; S_x, S_y: Two sided PSD functions of input and output. S_{xy}: Two sided cross PSD functions between input and output. G_x, G_y: One sided PSD functions of input and output. G_{xy}: One sided cross PSD functions between input and output. $G(\omega)$: One sided PSD function. γ_{xy}: Ordinary coherence between input and output. Θ_{xy}: Phase angle of one sided cross PSD functions. σ, μ: Standard deviation and mean value.

A. Cross Spectral Density Analysis between Piezo Output and Interaction force in X Direction

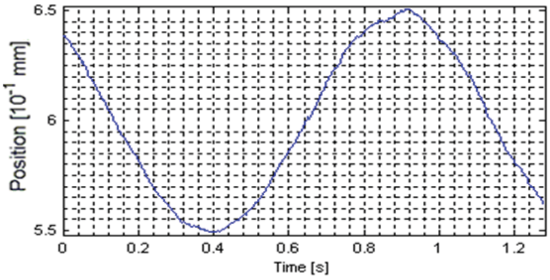

Fig. 6 One of the 54 samp. records of actual position of piezo actuator

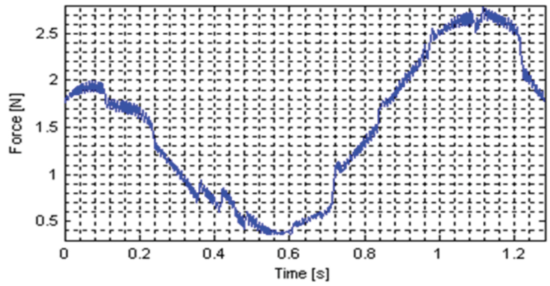

Fig. 7 One of the 54 samp. records of the interact. force in X direction

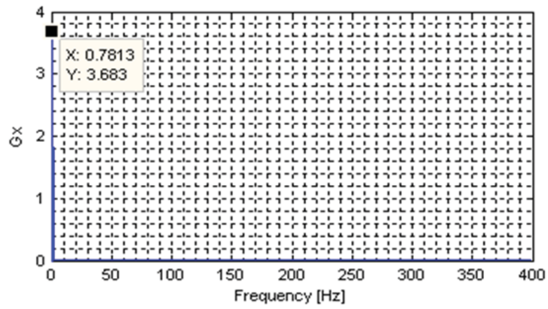

Fig. 8 Linear graph of one sided PSD func. estim. of actual piezo pos.

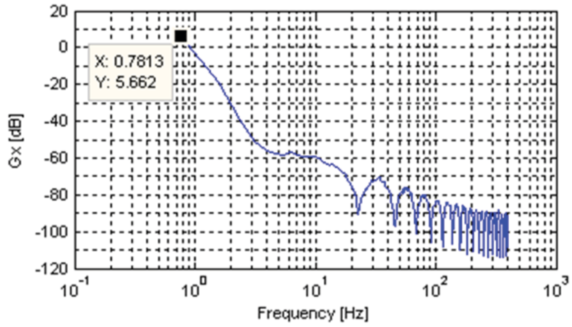

Fig. 9 Logarithmic graph of one sided PSD function estimate of actual piezo position

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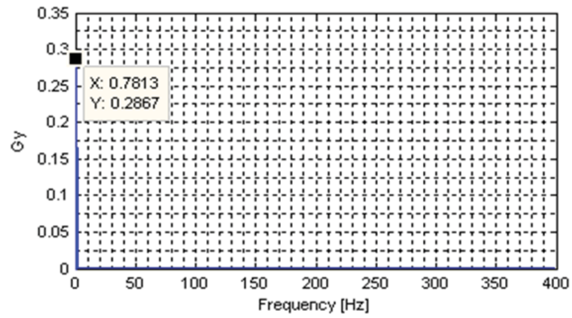

Fig. 10 Linear graph of one sided PSD function estimate of the interaction force in X direction

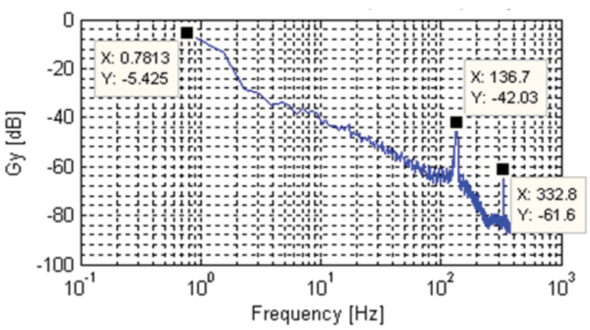

Fig. 11 Logarithmic graph of one sided PSD function estimate of the interaction force in X direction

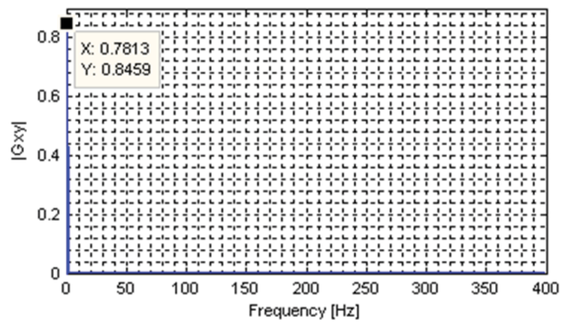

Fig. 12 Magnitude of one sided cross-PSD function estimates of actual piezo position and the interaction force in X direction

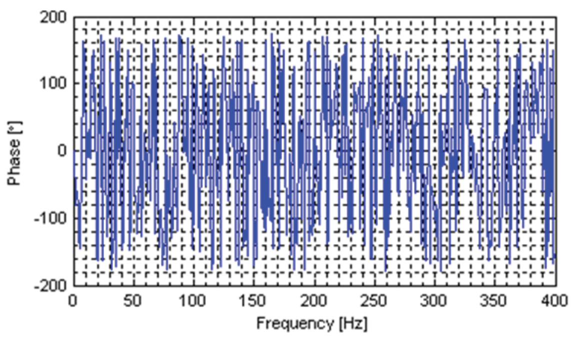

Fig. 13 Phase diagram of one sided cross-PSD function estimates of actual piezo position and the interaction force in X direction

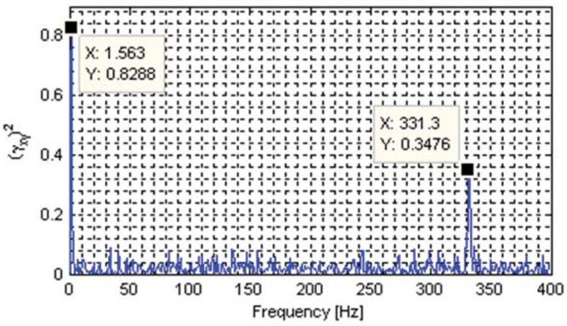

Fig. 14 Ordinary coherence function estimates between actual piezo position and the interaction force in X direction

The coherence value is 82,88% between piezo movement and the interaction force in x direction (Fig. 14).

B. Cross Spectral Density Analysis between Piezo Output and Interaction force in Y Direction

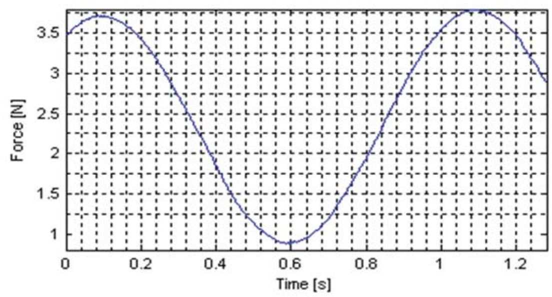

Fig. 15 One of the 54 sample records of the interaction force in Y direction which corresp.to the piezo pos. data sample shown in Fig.6

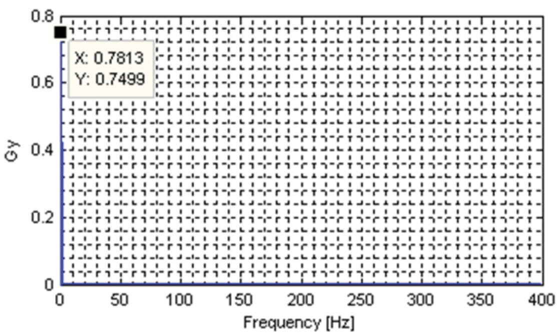

Fig. 16 Linear graph of one sided PSD function estimate of the interaction force in Y direction

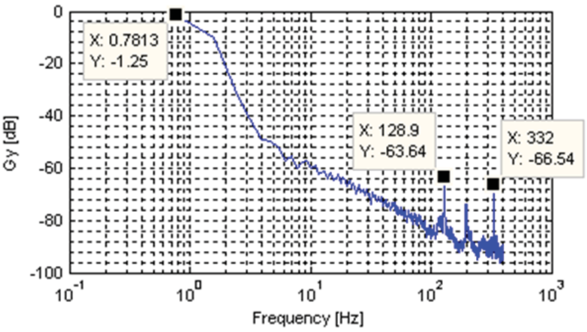

Fig. 17 Logarithmic graph of one sided PSD function estimate of the interaction force in Y direction

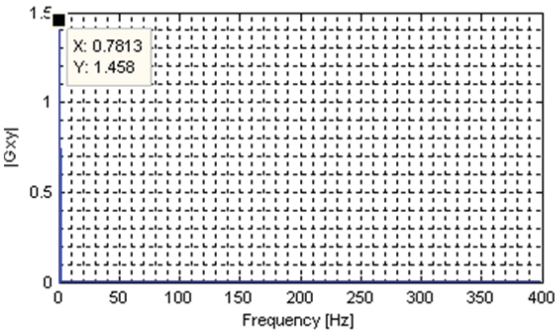

Fig. 18 Magnitude of one sided cross-PSD function estimates of actual piezo position and the interaction force in Y direction

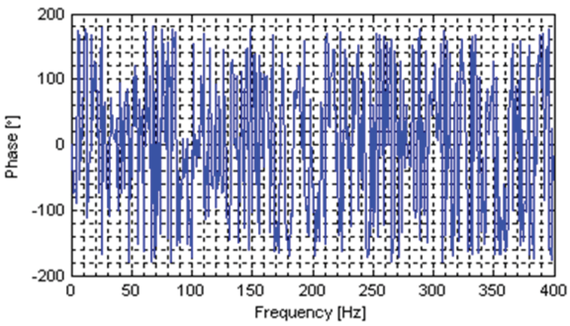

Fig. 19 Phase diagram of one sided cross-PSD function estimates of actual piezo position and the interaction force in Y direction

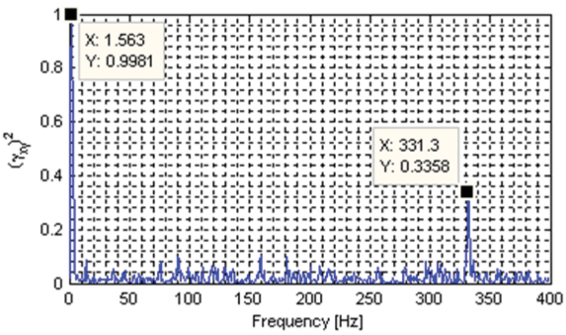

Fig. 20 Ordinary coherence function estimates between actual piezo position and the interaction force in Y direction

As it is seen in Fig. 20 the coherence value is 99.81% between piezo movement and the interaction force in x direction.

V. Results and Conclusion

In this work cross spectral analysis on the datasets obtained from grinding operation is performed. It has been shown that created interaction forces are correlated with the movement of piezo actuator at a certain level.

As a result, it has been proven that the coherence values are quite high. Especially, the result between the position of the piezo actuator and the interaction force in Y direction is almost equal to 1. This is an expected result since the only reason for grinding is the movement of the machining table and the tool. Also, because of the same reason, the frequencies in Figs. 8, 10 and 16 are the same.

In Figs. 14 and 20, the ordinary coherence estimate values at around 331 Hz are above 30% since 331 Hz is the frequency of the spindle speed (~20000 rpm).

Additionally, magnitude, spectral density function estimate and phase diagrams are presented.

Acknowledgment

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He was accepted at Robert Bosch GmbH, for his first internship in 2012. During this internship, he was in the maintenance - repair department. Secondly during his Erasmus period in Politecnico di Torino, he worked as a technical designer at Policumbent Team for 5 months. They built a recumbent tricycle. Then in 2013 he was accepted as an intern engineer at Ileri Model Fixture Die Design and Engineering Company, Bursa, Turkey. Additionally in 2013-2014 academic year, he worked on a quadruped robot project at Uludağ University. He is now working for "High precision hybrid robotic deburring system development" project, which is supported by the TUBITAK, 114E274. He is developing an active compliant motion controller for the machining table. His research interests focus on robotics, control systems and compliance control.

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