COMSOL MultiphysicsÈ Software for Simulation of Surface Response to Excitation Method for Manufacturing Process Performance Monitoring

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Abstract: In this study, COMSOL was used to simulate the surface response to excitation method (SuRE). SuRE is a structural health monitoring method that is developed for detection of various types of structural damages. This method also has been used to monitor manufacturing operations. SuRE is a frequency–domain technique similar to electromechanical impedance method where the changes in frequency transfer function are considered as damage indicators. An aluminum beam with a piezoelectric element bonded is modeled using COMSOL's piezoelectric module. The frequency spectrum of the structure is monitored through a frequency range of (20kHz-400kHz). A frequency domain sweep study was performed to simulate the sweep sign generation. A set of probe points measured the response to simulate the experimentations. In experimental tests laser scanning vibrometer measures the surface oscillations from a grid of scan points. The changes in spectrums of probe points due to milling, drilling and cutting operations are investigated using sum of squared differences (SSD) method.

Keywords: Frequency domain study, high-frequency surface waves, surface response to excitation, structural health monitoring, manufacturing process monitoring

1. Introduction

For many years structural health monitoring (SHM) techniques have been studied for improvement of reliability of engineering structures, reduction of periodical maintenance and prevention of unexpected failures [1]. Electromechanical Impedance method (EMI) [2] and Surface Guided Waves method [3] are two major trends in high-frequency based structural health monitoring. The former is frequency domain based and the latter is a time domain based technique. Surface response to excitation method [4] monitors the health of structure using characteristics similar to EMI method. A piezoelectric element excites the surface waves and another piezoelectric element or laser-scanning vibrometer monitors the surface waves in another point on the structure. Method has proved to be effective in detecting a variety of structural defects including tool wear [5], loose bolts [6] and compressive loads in beam [7] and plate [8] structures.

Manufacturing community has been using methods similar to SHM techniques for tool condition monitoring (TCM) [9]. Recently part-based manufacturing process performance monitoring (PbPPM) was introduced to monitor the manufacturing process based on the data collected from work piece [10]. The purpose of this method is to detect a various manufacturing problems including tool breakage, tool wear, chatter, and manipulator out of calibration, surface roughness etc. only bay monitoring the work-piece.

Analytical models for electromechanical impedance method are limited to simple structures like plate, beam and rod [11, 12]. Numerical modeling of EMI method has been subjected to previous studies in order to predict the crack growth or find the location of PZT transducers on the surface of structure. Coupled field analysis which takes both mechanical motions and electrical characteristics into account, was found to be the most efficient method for modeling complex structures [13, 14].

In this study the implementation of surface response to excitation method via non-contact optic sensor is modeled using COMSOL. The goal was to study the changes in frequency domain spectrum due to various manufacturing metal cutting operations through a frequency domain study. SuRE method has similar characteristics to transfer frequency response configuration of EMI method were more than one PZT is used. In this study there is a PZT for exciting the surface but instead of a second PZT, multiple probe points all over the surface of specimen measures the surface oscillations. This arrangement simulates a scanning laser vibrometer measuring high-frequency surface vibrations on a work-piece that is excited with a PZT element. Modeling of the non-contact implementation of SuRE method is necessary for design of an efficient and reliable manufacturing process performance monitoring system.

2. SuRE Algorithm

SuRE method creates a baseline measurement of surface response to sweep excitation in frequency domain. A SHM system based on SuRE method constantly measures these characteristics for all probe points and compares them to the values of baseline using the sum of the squared differences (SSD) index. If changes in SSDs exceed certain threshold the presence of damage to structure is speculated. In manufacturing process monitoring the purpose is to correlate the SSD to the operation so the presence, location and dimensional accuracy of operation and its status would be monitored. First the squared differences (SD) is calculated using:

$$\mathbf{D}_{m\times n} = \|\mathbf{A}_{m\times n} - \mathbf{R}_{m\times n}\|^2 = \left(a_{ij} - r_{ij}\right)^2 \qquad (1)$$

R and **A** are the baseline data and following data matrices, respectively. n is the number of or spectrums and m is the number of samples over the frequency range or each spectrum.

The sum of the squared differences (SSD) is calculated as sum of squared differences (SDs) for the entire frequency range:

$$\mathbf{S}_{1\times n} = \sum_{m} \mathbf{D}_{m\times n} = \sum_{i=1}^{m} {d_{ij}}^2 \qquad (2)$$

In this study, COMSOL simulates laser vibrometer monitoring surface accelerations during various metal cutting operations through a grid of scan on an aluminum beam. Figure 1 shows a schematic of aluminum beam, PZT exciter; 5×7 probe points and the metal cutting operations.

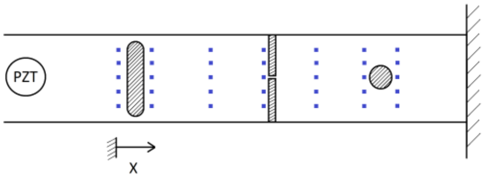

Figure 1. Schematic of aluminum beam with PZT exciter, scan probes and drilling, cutting and milling operations.

Based on the SuRE method first a baseline data was measured probe points. Subtracting material from the model simulated each manufacturing operations. Based on the SuRE method described in this section, the SSD values were calculated and compared to those of baseline at every step of operation. The behavior of surface waves and SSD values and their response to each operation were studied.

3. Use of COMSOL Multi-physics for Sure-based Manufacturing Process Performance Monitoring Method

The model in this study was an aluminum specimen with (2in)×(36in) beam and (1/16in) thickness. The piezoelectric is attached to the middle of the beam. Table 1 shows the dimension of materials and operations being used in the model:

Table 1: Dimensions of beam, piezo and operations

Property	Value
Length of Plate	36 [in]
Depth of Plate	2 [in]
Thickness of Plate	(1/16) [in]
Radius of Piezo	0.375 [in]
Thickness of Piezo	0.040 [in]
Radius of Hole	0.5 [in]
Location of Hole	30 [in]
Width of Cut	.05 [in]
Depth of Cut	0.95 [in]
Location of Cut	26.2[in]
Width of Milling	0.75 [in]
Depth of Milling	1.5 [in]
Location of Mill	22 [in]

The model has a simple geometry and was created in COMSOL's piezoelectric device module and investigated in a frequency domain study. The beam material is aluminum with density of 2700 kg/m^3, modulus of elasticity of

$70GPa$ and Poisson's ratio of 0.33. The piezoelectric element is Lead Zirconate Titanate (PZT-4) type with density of $7500\ kg/m^3$.

Although the physics of this study is piezoelectric devices, the physics of beam is set to linear elastic material to reflect the multi-physics nature of this study. According to experimentation boundary condition of both ends of the beam is fixed constraints and everywhere else is free. The lower surface of piezoelectric element is considered as ground with a zero charge and upper surface is charged with the piezoelectric element is charged with a 20 Volts. Figure 2 shows the geometry of the model of this study.

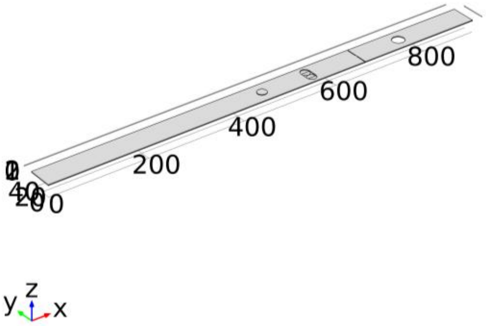

Figure 2. Aluminum beam model with a PZT element in center; drilling, cutting and milling are simulated.

The model meshed with free tetrahedral elements. The minimum mesh size was set 50mm and the maximum mesh size was set 500mm (Figure 3).

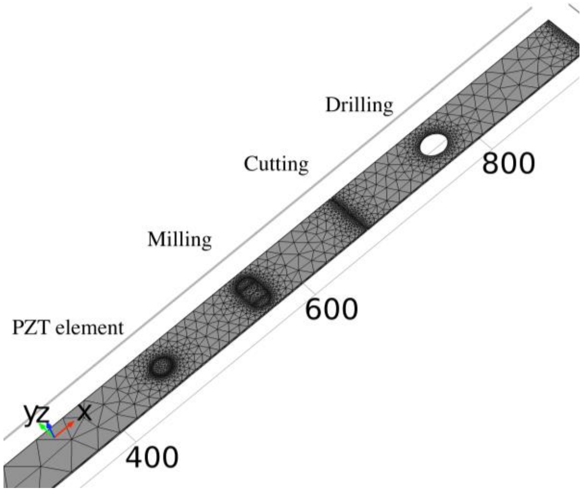

Figure 3. Meshed model with free tetrahedral elements.

The surface response to excitation method excites a sweep of high-frequency surface-guided waves on the work-piece and measures the instantaneous Fast Fourier Transform of the response in the probe points. To simulate this process of SuRE method, a frequency domain study was chosen and the frequency range of 20-400[kHz] with step of 1[kHz] was performed. The initial values of displacement and velocity for all points were zero. The amplitudes of response and their time derivatives of each probe point were obtained from the solution. The final solution includes the spectrum of transfer function for 35 probe points. The baseline data was obtained when the beam was intact and following data sets obtained after each of the drill, cut and mill was performed.

4. Simulation Results

Figure 4 shows a typical spectrum from a probe point resulting from simulation. The concept of SuRE method is based on the assumption of consistency of these spectrums in the absence of damages. Another characteristic of method is the local sensitivity of spectrum to the structural damages.

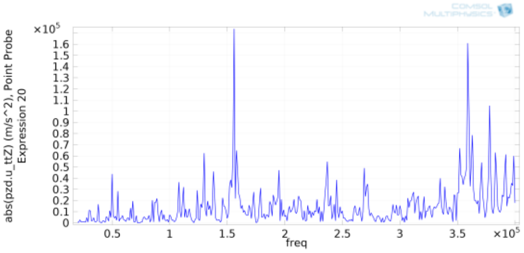

Figure 4. Accelerations vs. frequency in spectrum from a probe point.

In presence of a fatigue cracks the spectrum of probe points adjacent to crack will influenced more than the farther ones. This phenomenon is demonstrated in Figure 5 and Figure 6. Both spectrums compare the spectrums of before and after the drill hole was introduced to the beam. In Figure 5 the probe point is located on the 2nd probe column and the figure 6 the probe point is located on the 6th probe column.

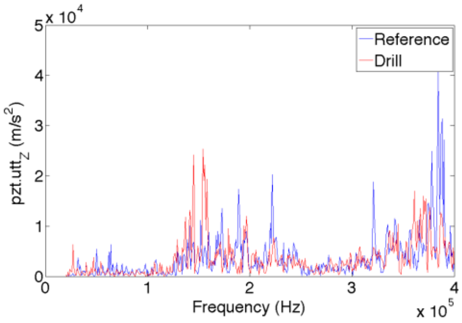

Figure 5. Spectrums of before and after the drill hole from a probe in 2nd column.

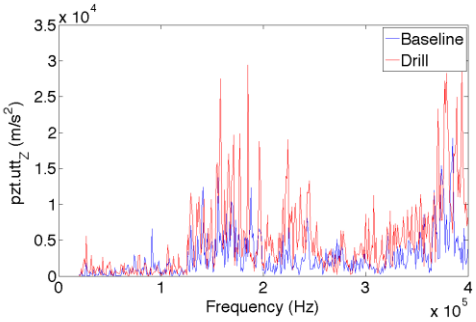

Figure 6. Spectrums of before and after the drill hole from a probe in 6th column.

Obviously both spectrums are influenced due to the presence of drill operation but the probe point in the 6th column is showing much more deviation from its initial condition.

According to schematic shown in Figure 2, the drilling operation was performed between 6th and 7th scan probes. Therefore, this phenomenon reflects the locality property of transfer function spectrums.

4.1 Drilling

Since the study was a frequency domain study, the solution set includes a set of displacements for each frequency starting from 20[kHz] to 400[kHz] with 1[kHz] step. Figure 7 shows the solution for displacements of the beam for the 1st frequency step, 20[kHz].

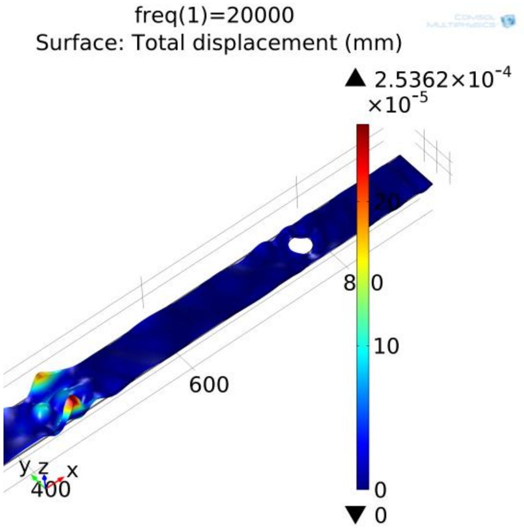

Figure 7. The drilling surface displacements solution for the 1st frequency step; 20[kHz].

While there is significant vibrations in the vicinity of piezoelectric, no considerable local change in the oscillations close to hole has occurred for the 20[kHz].

The advantage of SuRE method is that it is not limited to a single frequency and a range of frequencies is examined. Figure 8 shows the exaggerated displacements on the beam for 22[kHz].

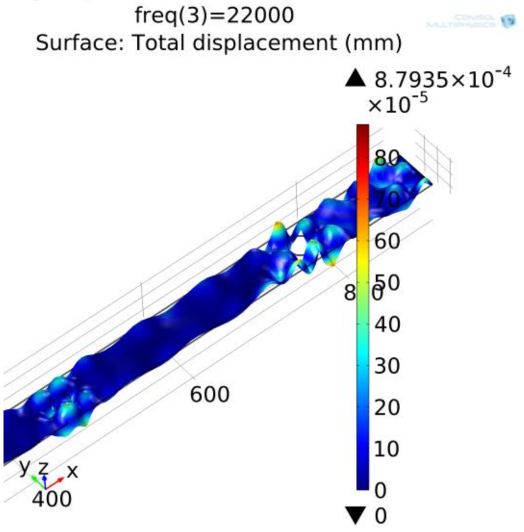

Figure 8. The drilling surface displacements solution for the 3rd frequency step; 22[kHz].

In 22[kHz] significant vibrations are surrounding the hole which means that this frequency to the creation of hole in this specific location of the beam.

SuRE method compares the spectrums of all probe points to the baseline ones using the sum of squared differences method as described in chapter 2. The bar diagram in Figure 9 shows the SSD values for all scan points after drilling.

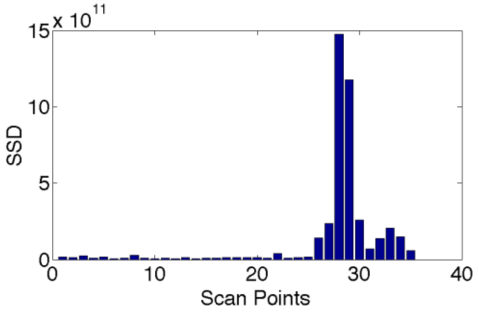

Figure 9. Bar diagram of SSD values vs. scan points for drilling.

The maximum SSDs are occurred in probe points 25-35. These probes are located in the 6th and 7th scan columns that are surrounding the drill hole.

Figure 10 gives another perspective of behavior of SSD values by demonstrating a color-map of them over the surface area of beam.

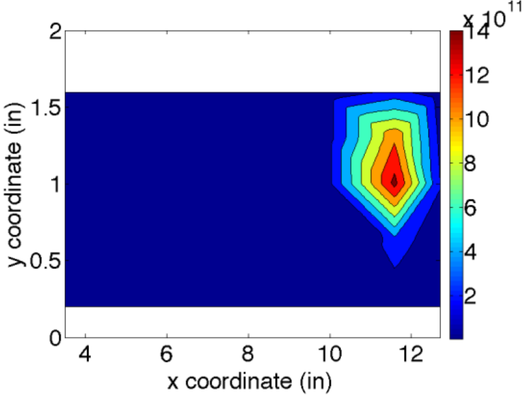

Figure 10. Color-map of SSD values vs. scan surface for drilling.

The color-map reveals the drill hole in the correct location.

Prior to this only the presence of machining operation could be estimated by monitoring the changes in the SSD values. Similar color-maps could be used for SuRE based manufacturing process monitoring systems to monitor the correct location of operation. A simple image processing could locate the position of red spot and compare it to programmed machining operation. Depending on the number for data points even it is possible to estimate the dimensional accuracy and surface quality using a higher definition of color-map.

4.2 Cutting

The cutting operation was a symmetric double cut type from ends of the beam's width. But the cut was not all the way through and small part still was connecting the left and right sides to the cut to each other. In this case, three distinguishable behaviors were observed in the way the surface waves reacted with the cutting edges.

Figure 11, 25[kHz] case, shows the beam in which the waves passed though the narrow connection in the cut without a considerable interaction with the cutting edges.

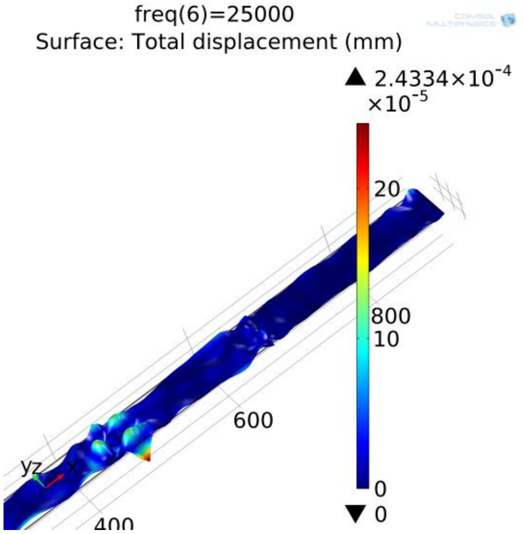

Figure 11. The cutting surface displacements solution for the 6th frequency step; 25[kHz]; waves passed thought cut without considerable interaction.

In Figure 12, 26[kHz] case, surface waves are reflected from the cutting edges creating a considerable oscillations on left side of the edge while the right side is pretty much calm.

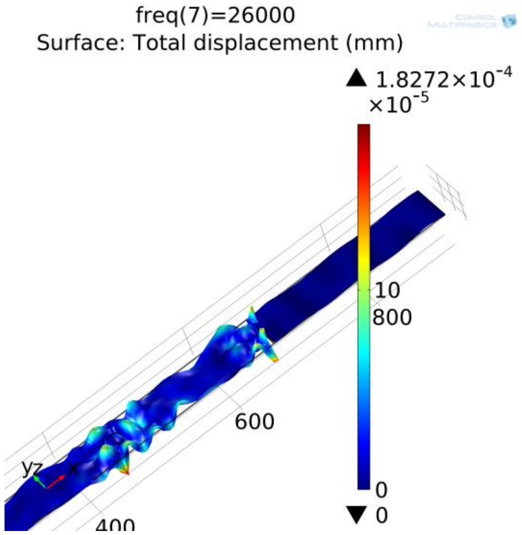

Figure 12. The cutting surface displacements solution for the 7th frequency step; 26[kHz]; waves reflected from cutting edge.

In the 3rd case the waves passed thought the cutting edge and created magnified amplitudes around the cutting edge. This case is shown in Figure 13 for 34[kHz].

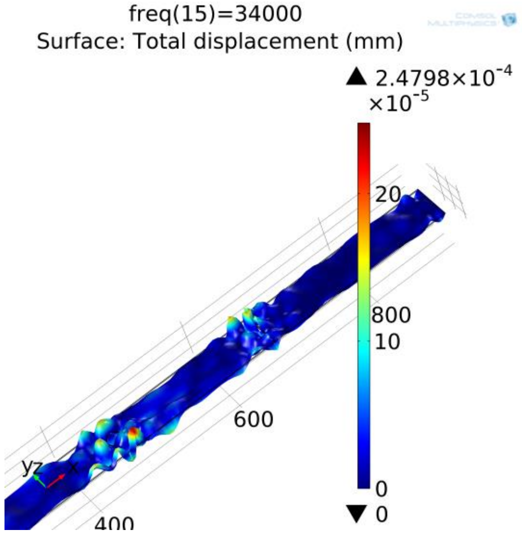

Figure 13. The cutting surface displacements solution for the 15th frequency step; 34[kHz]; waves passed thought cut with showing interaction.

In Figure 14 the color-maps of SSD values highlighted the cutting edges correctly in the middle of scan area.

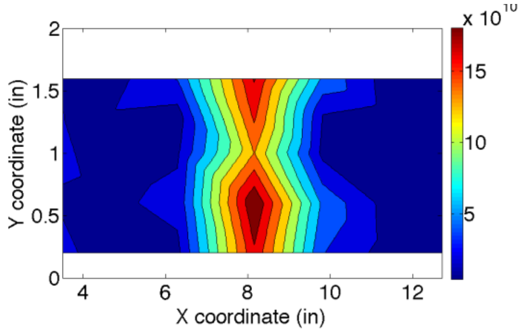

Figure 14. Color-map of SSD values vs. scan surface for cutting.

The bar diagram of SSD values in figure 15 shows the values increase in probe points close to the cutting edges.

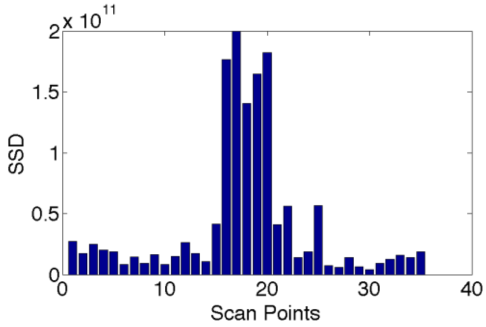

Figure 15. Bar diagram of SSD values vs. scan points for cutting.

4.3 Milling

The milling operation was the closest operation to the location of piezo in the middle of beam. Figure 16 shows that the oscillations adjacent to milling operation are combined to those around the piezo. This phenomenon shows that in order to have consistent measurements the location of piezo element should be chosen in a reasonable distance from manufacturing operations.

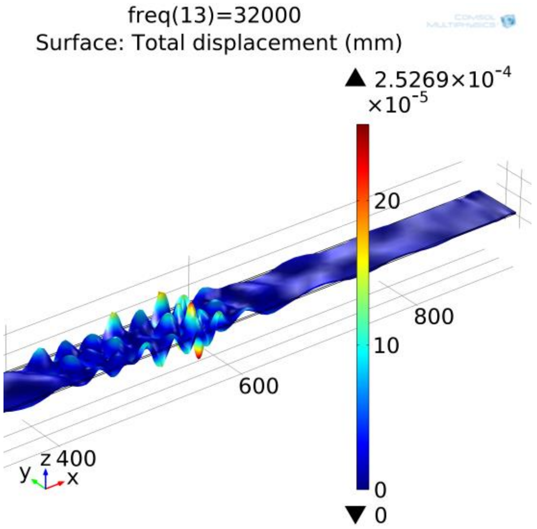

Figure 16. The cutting surface displacements solution for the 14th frequency step; 32[kHz]; waves interacted with milling are mixed with vibrations around piezo.

Figure 17 and Figure 18 show the SSD values for scan points and their color-map over for the case of milling operation.

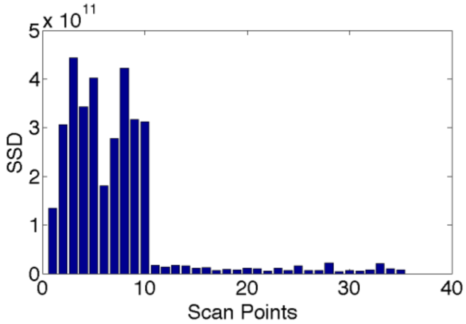

Figure 17. Bar diagram of SSD values vs. scan points for milling.

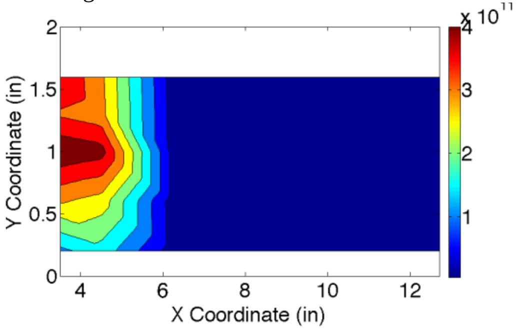

Figure 18. Color-map of SSD values vs. scan surface for milling.

Although the location of operation is identified correctly, its boundaries is not clearly specified due to the combination of large amplitudes coming from piezo.

7. Conclusions

In this study, COMSOL was used to investigate the non-contact implementation of surface response to excitation method for monitoring manufacturing machining operations. The model was created by appropriately dimensioning a thin aluminum plate with a cylindrical piezoelectric device bonded to the middle. Using the piezoelectric device physics module in COMSOL we were able to define the experimentation parameters such as boundary conditions and material properties. The piezoelectric physic module also allowed us to define the terminal as well as a ground location, in which we applied a voltage load in order to excite the surface waves on the beam via piezo device. Point probes defined on a grid of scan point, which measured the acceleration and created the baseline frequency spectrum. The effects of machining operations on the frequency spectrum were simulated. Sum of the squared differences method was used to compare the altered spectrum to those of baseline. The contour map diagram of SSD values confirmed the experimental observations. After each operation the maximum changes in manufacturing occurred in the vicinity of that operation. The existence, the shape and the location of the operation could be estimated with the contour maps. Also COMOL's surface displacement solution successfully revealed the difference cases of interaction of surface waves with the machining operation for each frequency.

8. Acknowledgement

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