INDEPENDENT JOURNAL OF MANAGEMENT & PRODUCTION (IJM&P)
http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

TOOL AND WORKPIECE VIBRATIONS MEASUREMENT - A REVIEW

PBGSN Murthy
Vignan's Foundation for Science, Technology, and Research Deemed to be University, India
E-mail: pbgsnmurthy@gmail.com

Ch Srinivasa Rao
College of Engineering, Andhra University, India
E-mail: csr_auce@yahoo.co.in

K Venkata Rao
Vignan's Foundation for Science, Technology, and Research Deemed to be University, India
E-mail: kvenkatrama@gmail.com

Submission: 20/03/2018
Revision: 11/04/2018
Accept: 23/04/2018

ABSTRACT

Tool condition monitoring is one of the important aspects in machining process to improve tool life. It comprises three important steps namely machining data acquisition, data analysis and decision making. Vibration in metal cutting has direct impact on the tool life as well as surface roughness. The present study focused on measurement of vibration during the machining process. Data acquisition is made by using various types of sensors. A wide variety of technologies like contact and non-contact sensors have been used for real time data acquisition of tool or workpiece vibrations. Research works carried out by many authors is highlighted in measurement of cutting tool and machine tool vibrations using different sensors. Influence of various input parameters like tool geometry, feed, speed and depth of cut on the magnitude of vibrations is discussed. Influence of vibration on surface roughness, tool life and power consumption is reviewed. Three dimensional vibration measurement with single Laser Doppler Vibrometer is also covered for precise analysis of vibration.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

Keywords: Tool condition monitoring, tool vibration, tool life, sensors, Laser Doppler Vibrometer.

1. INTRODUCTION

Tool Condition Monitoring (TCM) is an essential requirement in advanced manufacturing process to monitor the performance of cutting tools. Machining process is a complex dynamic process where the tool wear is the most undesirable characteristic which severely affects the tool life.

Tooling cost plays a vital role in the overall cost of production. TCM is an important area to reduce the tool failure and machine break downtime. Reduction of machine tool break downtime enhances productivity and reduces production cost. Worn tool results in rough surface of work piece, dimensional inaccuracies and also vibrations during the machining. Early replacement of a workable tool or late replacement of a worn tool may cause low productivity and production loss (DAVID,JOHN,2006).

Hence, it is very important to improve the tool life and its performance by continuous monitoring. Milling, drilling and boring processes are difficult machining processes when compared to other machining processes. In these processes, tool vibration induced by cutting forces influences the tool life and surface quality of component.

Rigidity of tool holder is one of the significant parameters that influence dynamic stability of cutting tool. The tool holders have less rigidity in operations like drilling, boring and milling because of their longer length. David and John (2006) treated boring bar as a cantilever beam which is rigidly fixed to the machine tool and its deflection is evaluated by the equation (1).

$$\delta = \frac{F_r . L^3}{3 . E . I} \qquad (1)$$

where, F_r is radial force in Newton's, L is boring bar length in millimeters, E is modulus of elasticity in N/mm^2 and I is area moment of inertia in mm^4.

Insufficient rigidity of tool holder and work piece during machining causes spring back and it results in deflection of tool holder. Diameter of bored hole is reduced by metal spring back and tool marks formed on the machined surface due to

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

tool vibration. David and John (2006) recommended that shifting of cutting edge position with an amount of 0.02 to 0.04 mm reduces spring back and chatter. Length to diameter ratio (*overhang ratio*) of boring bar influences the resonant frequencies and chatter resistance. Boring bars with more than 4overhang ratio results in chatter. Stiffness of the tool holder can be improved by decreasing the overhang ratio or increase in size of tool holder for the same length of tool (VENKATARAO; MURTHY, 2016).

All bodies possessing mass and elasticity are capable to produce vibrations. Vibrations are defined as the repetitive motion of a body relative to a stationary frame referred to equilibrium of the vibration. Inman (2001) stated that there is a large impact of vibrations on the surrounding environment.

Figure 1.isdepicting a schematic representation of simple one degree of freedom damped vibrating system. A vibration that occurs due to continuous application of external forces is known as forced vibration. Some examples under this category are vibrations generated in machine tools, gas turbines , IC engines , pumps and compressors etc.,

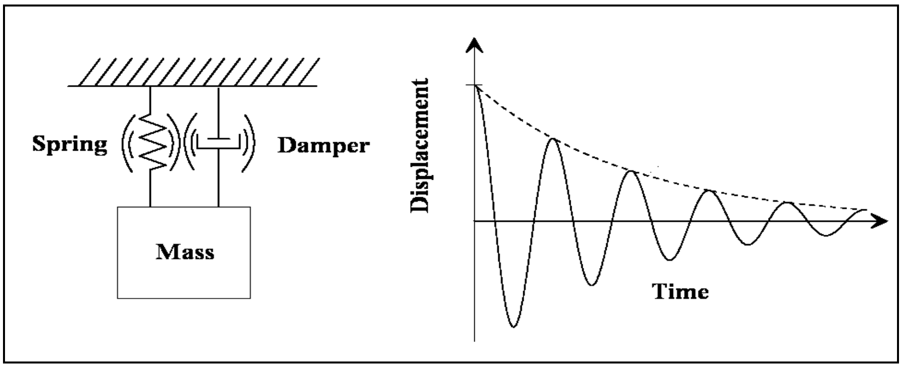

Figure 1: Single degree of freedom system
Source: Inman (2001)

Vibration analysis is made by measuring three parameters named as displacement, velocity and acceleration and they are used to estimate integrity of machine tool. Sensitivity of the measuring instrument depends on the frequency of vibrations. Low frequency vibration signals are usually measured by amplitude sensors.

Medium and high frequency vibrations are measured by velocity and acceleration sensors respectively. Monitoring of Vibration signals became an important technique in machine maintenance and quality control. Frequency of

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

vibration signals are used to identify source of defect and the amplitude of vibration is used to estimates intensity of the defect.

Finally, the vibration signals are very much useful to identify the condition of equipment or machine for further diagnosis of the problem. In some machining process like milling, turning and drilling etc., vibrations alters the machining characteristics such as surface roughness, dimensional accuracy and tool life. Production cost and productivity are also influenced by tool vibrations which are induced in machining process.

Andren et al. (2004) described various deformation zones in machining process as primary, secondary and tertiary zones. Primary deformation zone leads to stress and strain in the work piece, in remaining two deformation zones, shear and normal traction loads are applied on the tool due to friction and plastic deformation. Tool holder will undergo vibrations due to above said loads.

Researchers have carried out different studies on cutting tool vibration in different machining processes and dynamic modeling of cutting tool was also carried out. Many of the researchers have focused on optimization of cutting parameters to reduce the tool/workpiece vibration and prediction of stability limits.

Akesson et al. (2007) proposed three methods to improve boring bar stability to get good surface quality as well as production rate. They studied dynamic behavior of clamped boring bar by three methods such as experimental modal analysis, analysis of deflected shape during operation and the analysis of Euler–Bernoulli beam model. It was concluded that bending motion of boring bar is more in the direction of cutting speed. A good correlation among the results of three methods was found.

Chang (2001) reported that the tool life and surface finish are strongly influenced by frequency and amplitude of vibration. He concluded that the tool geometry plays an important role in the generation of tool vibration. Luke et al.(2001) pointed that two types of vibrations were induced during machining. They are forced and self-excited vibrations. Forced vibrations are caused by backlash in gear drives, inaccuracy and misalignment of machine tool parts etc. Self-excited vibrations are caused by chatter and mutual interaction between the insufficient rigidity of machine tool.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

This leads to disturbances in cutting zones. Tool vibrations are categorized based on driving force as regenerative and non-regenerative. According to Tobias (1965) regenerative chatter occurs due to undulation of surface texture produced in the preceding passes and non-regenerative chatter is due to plastic deformation of workpiece and friction at tool chip interface.

The present study is focused on effect of the process parameters on the vibration of workpiece as well as cutting tool in different machining processes. Effect of tool vibration on the surface roughness, cutting forces and tool wear is also discussed. A detailed review is made on findings of different researchers in turning and milling operations. Measurement of vibration and sensors used in the measurement are also reviewed.

2. EFFECT OF VIBRATION IN METAL CUTTING

Dimensional accuracy and surface finish of a machined component depends on machining parameters, feed, cutting speed, depth of cut and tool geometry. It also depends on method of machining, tool and work piece material. In addition to them, tool vibration also plays a vital role on the performance characteristics of machining as well as tool life. Surface roughness is not only affected by the process parameters, but also affected by the excess tool vibration, friction and built up edge.

Thomas and Beauchamp (2003) investigated the influence of machining parameters, cutting speeds, feed rates, depth of cuts, tool projected lengths from tool post, tool geometry and length of work piece on cutting tool stiffness and damping in turning of mild steels. In addition to that empirical model was also developed to identify the behavior of tool stiffness variation on each parameter. They concluded that the high cutting speeds and feed rates result in tool vibration.

Xiao et al. (2003) investigated the effect of tool nose radius on tool vibrations and surface finish. They suggested large tool nose radius for the improvement of tool strength, surface finish and to reduce vibrations. Correlation between tool vibration and tool wear in milling of AISI D3 cold work steel was investigated by Sadettin et al (2007).

Tool wear and tool vibration were measured with toolmaker's microscope and accelerometers respectively. Vibrations were measured in the machining direction because it is more dominant than the other two directions. Increase of tool wear

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

results increase in the vibration amplitude and significant amount of amplitude was found when the flank wear exceeds 160μm.

Kourosh and Per(2008) pointed out that the monitoring of tool vibration is highly essential in order to control the machining characteristics of high speed milling through online vibration data acquisition system. For an effective measurement of tool vibration and analysis of vibration, Laser Doppler Vibrometer (LDV)was proposed.

Alonso and Salgado (2008) used tool vibration signals to develop a TCM system which is reliable and faster. Experimental data of tool vibration and tool wear at different levels of process parameters were used to develop mathematical models for tool vibration and tool wear using artificial neural networks. In addition to that, vibration data was also analyzed using cluster analysis and singular spectrum analysis to predict the tool vibration.

Salgado et al.(2009) studied effect of tool vibration on the surface roughness in turning process. They conducted experiments at different levels of cutting speed, feed, depth of cut and tool geometry. During the process, vibration of the tool was measured using accelerometer and vibration signals were analyzed. Using the experimental results, statistical models were developed for the surface roughness in terms of the process parameters and tool vibration to predict surface roughness.

They concluded that the nose radius is more significant parameter among the other selected parameters on the tool vibration as well as surface roughness. Ostasevicius et al. (2010) identified tool vibration has more influence on the surface finish of a machined component. Andren et al. (2004) and Miguelez et al.(2010) investigated the dynamic characteristics of boring tool holder in boring of steels and cast iron. Vibrations were measured in the directions of cutting speed and depth of cut using accelerometers.

It was found that first resonant frequency influences the vibration magnitude in one direction. Wang and Chan (2013) studied the effect of tool-tip vibration on surface finish in ultra-precision diamond turning. Representative measurement method was used to measure the surfaces produced by single point turning and observed turning marks on the work piece and spatial errors in radial direction measurement.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

3. MEASUREMENT OF TOOL AND WORKPIECE VIBRATION

This section describes various vibration measurement methods in different machining operations. Acoustic Emission (AE) is defined as spontaneous release of transient elastic energy in materials undergoing deformation and fracture. AE signals were used to estimate tool vibration in machining processes like boring, drilling, milling and turning process. Dornfeld and Kannatey (1980) used contact type piezo-electric transducer to measure vibration of machine tools in the form of AE signals while machining is in progress.

Tool life is influenced by various parameters like tool geometry, tool material and length of tool holder etc., Tool wear is more predominantly influenced by length of boring bar in boring process because boring bar is subjected to vibration. Abdul and Sivakumar (1987) reported that the rubbing between tool and work piece causes noise spectra of low frequency.

This data was used to investigate the effect of cutting speed and tool overhang on flank wear. They concluded the overhang length is the significant parameter on tool wear. Roberto and Micheletti (1989) evaluated flank and crater wear using AE signals in turning process to analyze tool wear. Tool vibrations, tool wear and surface roughness of machining component during machining was estimated by analyzing the induced acoustic emission signal.

Chang and Richard (1989) used root mean square (rms) of tool vibration velocity to evaluate tool wear at high cutting speeds of machining with ceramic tools. Based on the rms value of AE signals, it was concluded that the base of tool tip is the most sensitive to tool wear.

Ngoi and Venkatakrishnan(2000) investigated the influence of vibrations in machining of micro size components machining like dimensional accuracy and surface finish. Laser Doppler vibrometer (LDV) was used to measure vibrations in machining of micro components.

The LDV measures vibrations in the form of acousto optic emission signals (AOE) after that theseAOE signals were processedusing Fast Fourier transformation

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

(FFT) to read amplitude of tool vibration directly. Vibration of a rotating work piece and cutting tool can be measured in terms of amplitude, velocity and acceleration. In TCM, vibration of tool/work piece is one of the major factors which is to be controlled.

There are two types of sensors used to measure vibration of work piece and cutting tools; contact and non-contact sensors. Researchers have been adopting different kinds of technologies in measurement of vibration namely vibration sensors, touch sensors, AE sensors, power sensors and vision sensors etc. (XIAOLI, 2002; DIMLA et al., 2000).

Prasad et al.(2010) used a novel technique for real time process monitoring using multiple sensors signals such as LDV and infrared thermal cameras to obtain vibrations, temperature and tool wear measurements. Figure 2 shows measurement of vibration of rotating workpiece with the LDV.

The LDV is placed in front of the machine at proper position and laser beam was focused on the workpiece to measure its vibration. This proposed TCM system was designed to evaluate the high speed turning operation on AISI 316L steel with coated and uncoated CNMG 150608 type carbide inserts. Vibration signals were obtained using a LDV and the vibration signals were analyzed.

Cheran and Jia (2007) used vibration cutting to find the effect of tool vibration on surface roughness in boring and drilling process. Shading area method was proposed to analyze burrs in intersecting holes. They concluded burrs and holes were reduced due to the use of high frequency vibration boring and ultimately improves the surface finish.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

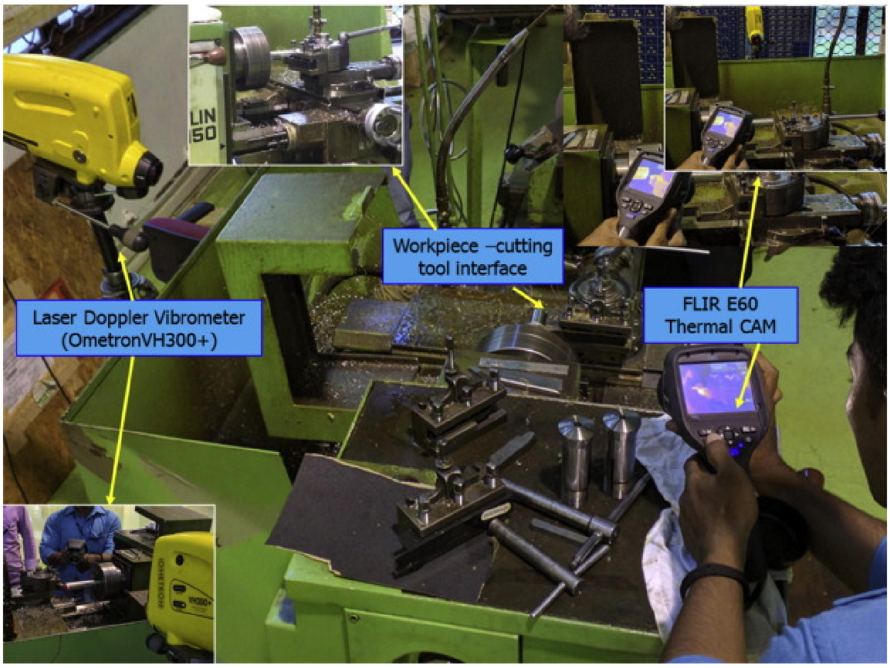

Figure 2:.Experimental test setup in central machine shop
Source: Prasad, Sarcar and Satish (2010)

4. CONTACT TYPE SENSORS

Contact type sensors are the devices require physical contact with the object. They measure vibration of cutting tool, work piece and machine tools. Contact type sensors are attached to a vibrating body to measure vibration and also to convert the mechanical vibration magnitude into electrical signal. Electrical signal is processed into measurable characteristics like amplitude, frequency and phase.

Accelerometers, velocity and displacement transducers are used commonly to measure vibrations (ZAHIA et al., 2013). Rahim et al., (2009) developed a micro electro mechanical system accelerometer to measure vibration of machine tool. Chih et al., (2012) described an appropriate control of machining with the development of a decision making methodology using signals calibration.

Singular spectrum analysis(SSA) was used to extract and transform the raw signals of vibrations on the cutting tool for investigating the relationship between tool vibration and surface roughness in precision end milling of SCM440 steel. Three accelerometers were used at a time on the tool holder of mill cutter to sense the vibration of spindle in X, Y and Z directions. The vibration data was used to develop a correlation between surface roughness and vibration. A mathematical model was also developed to identify the critical parameter which affects the vibration.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

Chelladurai et al., (2008) used two accelerometers to measure cutting tool vibrations in two different directions. As shown in the Figure 3, two accelerometers were fixed on tool holder in the directions of feed and cutting. They used the vibration data along with strain data to study the tool flank wear in turning process.

Andren et al., (2004) studied vibrations induced in the boring bar while boring alloy steel, stainless steel and cast iron. Vibrations were measured in both the directions of cutting speed and depth using two accelerometers.

Ghani et al (2002) performed machining on nodular cast iron to study the effect of tool wear and vibration on surface finish using ceramic tools. Two accelerometers were used to measure vibrations of cutting tool. One accelerometer was placed in main cutting force direction and the other one was placed in radial cutting force direction.

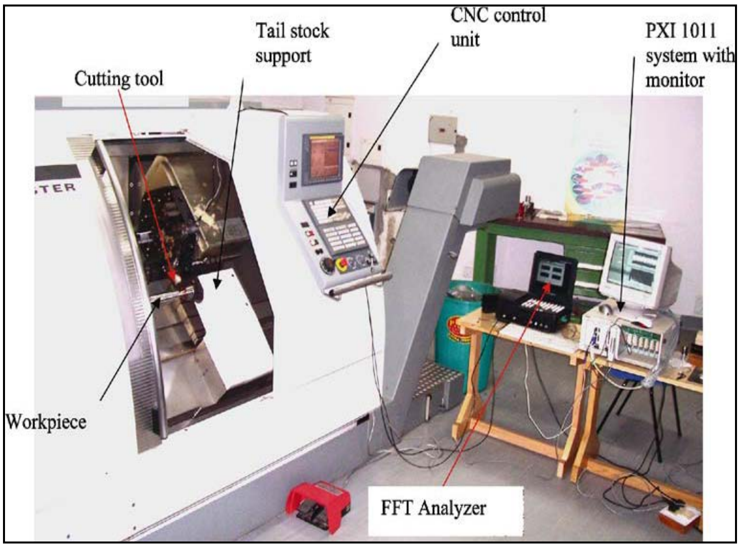

Figure 3: Vibration measurement using accelerometers
Source: Chelladurai, Jain, and Vyas (2008)

Sivasakthivel et al., (2011) also used two accelerometers to measure acceleration and amplitude of spindle and work piece vibrations while machining aluminum A16063 with HSS end mill cutter. As shown in the Figure 4, one accelerometer was kept on work holder and the other one was placed on spindle to measure vibrations in feed as well as axial cutting directions respectively.

A mathematical model was developed with cutting parameters such as helix angle, feed rate, spindle speed and depth of cut. This mathematical model was used to develop a relation between end mill cutter vibration and cutting parameters. They

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

found that the helix angle has more influence on the amplitude of acceleration and at $45^0$of helix angle, the vibration amplitude was found to be minimum.

Accelerometers are widely used instruments to measure acceleration of tool and work piece in contact type sensors category. Dynamic characteristics are evaluated by analyzing acceleration and excited load signals using various digital signal processing techniques. There are several difficulties and disadvantages found with contact type sensors in vibration measurement.

It is difficult to measure vibrations of rotating bodies like work piece in turning operation (both external and internal), tools like drill bits, milling cutters and grinding wheel etc. Some of the disadvantages mentioned by Dongkyu Kim et al., (2013) are loading effect on frequency response in case of light and flexible structures, tethering problem in measurement and sensitivity to electromagnetic interference effects. To overcome these difficulties, non-contact type sensor measuring devices are preferred.

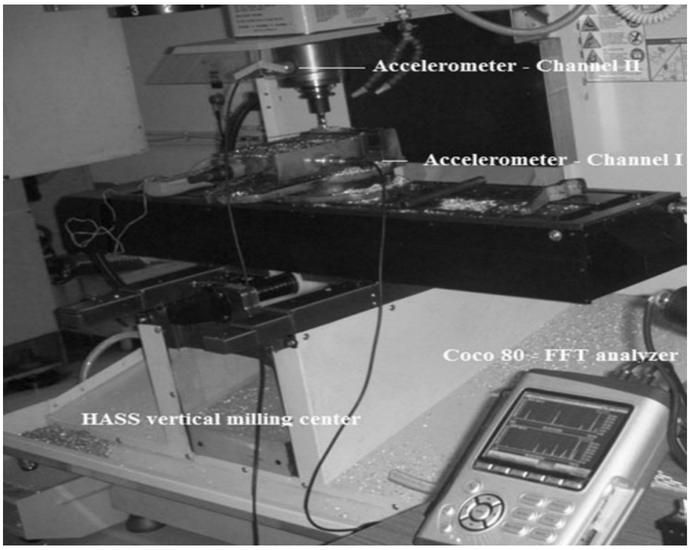

Figure 4: Experimental setup for vibration amplitude measurement
Source: Sivasakthivel, Velmurugan and Sudhakaran (2011)

5. NON-CONTACT SENSORS- LASER DOPPLER VIBROMETER

Vibration measurement of moving elements such as gears, shafts, pulleys, cutting tools in drilling and milling machine are difficult with contact type sensors. Low magnitude of rotor vibrations measurement is also difficult with contact type sensors. According to Bell and Rothberg (2000) measurement of rotating elements, hot and light components is easy and simple by noncontact sensors. In these cases,

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

vibration measurement can be carried by non-contact type sensor like Laser Doppler Vibrometer (LDV) (EWINS,1984; VENKATRAO et al., 2013; BALAJI et al., 2018).

In early days, LDV was used to measure turbine blade vibrations. LDV consists of three measuring scan heads which are capable of measuring the movements in the three orthogonal directions to obtain full information of the three dimensional movements. The LDV works on the principle of Doppler effect and interferometry for vibration measurement.

The LDV system software controls the entire measurement process with graphical user interface. LDVs can measure vibrations up to 30 MHz range with very linear phase response and high accuracy. Based on laser Doppler principle, two types of instruments exist to measure vibrations. They are Continuous Scanning LDV (CSLDV) and Tracking LDV (TLDV).

5.1. Working principle of Laser Doppler Vibrometer

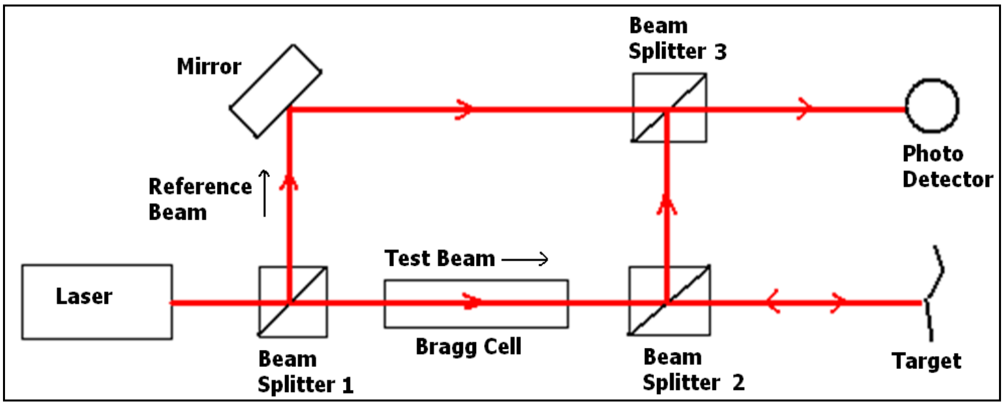

Figure 5: Typical components of a Laser Doppler Vibrometer
Source: Venkatarao (2014)

A laser beam produced by the LDV is focused on a vibrating surface and it is reflected from the vibrating surface. Doppler shift of the reflected laser beam frequency is used to find out frequency and amplitude of the vibrating target. Output The LDV is continuous analog voltage and it is directly proportional to the velocity of vibrating target. LDV device is mainly operated with Helium-neon lasers.

Laser beam which is focused on target i.e., vibrating surface is initially spited into reference beam and test beams by beam splitter 1 with the initial frequency of (f_o) shown in Figure 5. Reference beam moves vertically towards mirror and reflected towards beam splitter3 and then to photo detector (VENKATRAO, 2014). Test beam

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

passes through the Bragg cell where frequency shift (f_b) is added to the target beam. This beam targets the vibrating body (Target) with a frequency ($f_o + f_b$). The motion of the vibrating body (target) adds a Doppler shift to the beam and its magnitude is given below:

$$f_d = \frac{2\,v(t) Cos\alpha}{\lambda} \quad (2)$$

Where v(t) is the velocity of the target,

$\alpha$is the angle between velocity and vector laser beam, and

λ is the wavelength of the laser beam.

Vibrating target scatters the light and part of the scattered light reflects back to the beam splitter 2 and directed to beam splitter 3and then reflected towards photo detector. Frequency of this beam is equal to ($f_o + f_b + f_d$). This reflected scattered light is combined with reference beam at photo-detector. The output signal which is obtained at Photo detector is converted into frequency modulated (FM) signal. FM signal is demodulated to obtain velocity vs. time of the vibrating target.

5.2. Measurement of vibration with LDV

Prasad et al. (2010) developed an online tool condition monitoring system for face milling operation to monitor effects of tool/workpiece displacement caused by vibration. A relationship between process parameters and the tool vibration, tool wear and surface roughness was developed. Vibration data of rotating tool and work piece is collected with different sensors and transferred to a computer through a data acquisition system in LDV assisted vibration measuring method.

Figure 6 shows the measurement of rotating mill cutter vibration by focusing laser beam on the tool. Data acquisition system comprises of a LDV, a highly accurate and versatile non-contact vibration transducer for measuring the vibrations during machining (VENKATRAO, 2014). The output signal of the LDV serves as an input for FFT analyzer where signal analysis is done.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

Figure 6 :Measurement of rotating work piece vibration using LDV
Source: Venkatarao, Murthy and Mohanrao (2014)

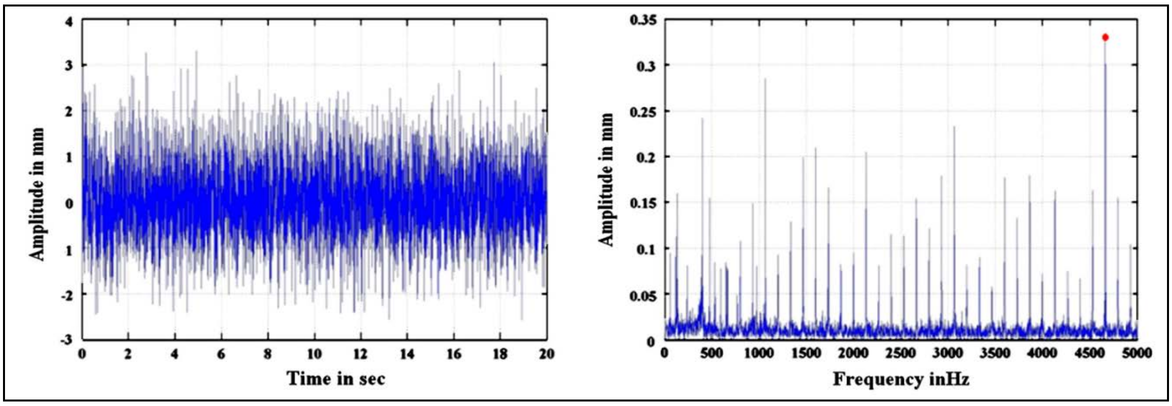

Figure 7: Time and frequency domain spectrographs
Source: Venkatarao, Murthy and Mohanrao (2014)

During the machining, amplitude of work piece vibration is measured with LDV (BELL et al., 2000; VENKATRAO et al., 2014; ROBERTO et al., 2000; CASTELLINI et al., 2000). As shown in the figure 7, vibration data is collected from the LDV in the form of time domain spectrograph. It is difficult to identify maximum amplitude of work piece or tool vibration from the time domain spectrograph, so the time domain spectrograph is converted into the frequency domain spectrograph using FFT analyzer to identify the amount of amplitude easily.

6. THREE DIMENSIONAL VIBRATION MEASUREMENT

Dongkyu Kim and Kyihwan Park (2013) have designed a pseudo 3D Laser Scanning Vibrometer (LSV) to measure vibration of a surface in three directions at a time. In this system, a light detection and ranging (LIDAR) device combined with the LSV along with an optical filter is used. This system produces three laser beams at a time to measure vibration of a surface in three directions. But it involves more investment on the equipment.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

6.1. 3D Vibration measurement with single LDV

It is possible to measure vibration of a surface in three dimensions with a single LDV. It reduces extra investment on 3D LDV. Dongkyu Kim et al (2014) have developed a technology to achieve three dimensional vibration measurement with one LDV. In this technique three dimensional vibration measurement is made by moving the LDV in three different locations.

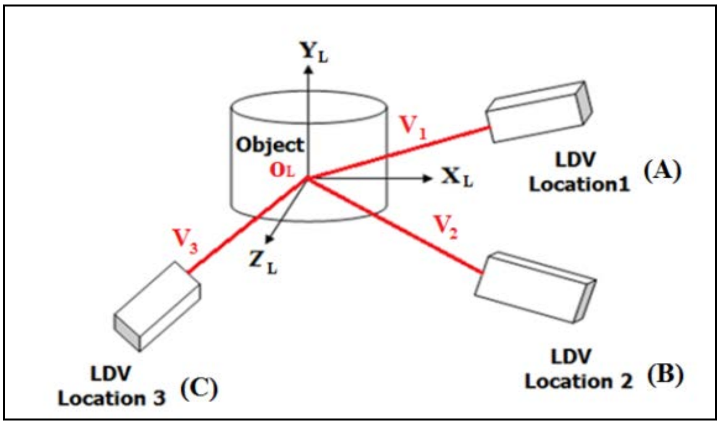

Figure 8: Vibration measurement at arbitrary point on object from three different locations
Source: Dongkyu, Hajun, Hossam, Jongsuh, Semyung and Kyihwan (2014)

Figure 8 shows different measurement locations to measure vibration of an object at one point O_L. That point is defined as origin of local coordinate system (X_L, Y_L, Z_L) of the object. V_1, $V_2$and V_3 are the measured vibration of the object at A, B and C locations respectively. Position A is defined with respect to the local coordinate system as follows:

$\bar{A} = a_x i_x + a_y i_y + a_z i_z$---------------- (3)

where a_x, a_y, and a_z are coordinates of A and i_x, i_y and i_z are unit vectors on the local coordinate system. A position with respect to a general coordinate system is defined as follows:

$\bar{A'} = a'_x i'_x + a'_y i'_y + a'_z i'_z$----------------- (4)

Components of A with respect to general coordinate system are found through the dot product of the two point vectors as follows:

$\bar{A}.\bar{A'}$------------------- (5)

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

$$\begin{bmatrix} a'_x \\ a'_y \\ a'_z \end{bmatrix} = \begin{bmatrix} i'_x i_x & i'_x i_y & i'_x i_z \\ i'_y i_x & i'_y i_y & i'_y i_z \\ i'_z i_x & i'_z i_y & i'_z i_z \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \text{-------------- (6)}$$

The equation (6) is a relationship that expresses how the components of position of point vector A in local coordinate system relate to the same components of the same point vector in a general coordinate system. Then,

$i'_x i_x = Cos\theta'_{xx}$-------------------- (7)

In the above, θ'_{xx} represents angle between X axis of local and general coordinate systems in X direction, θ'_{xy} is the angle between X axis of local and general coordinate systems in Y direction and θ'_{xz} is the angle between X axis of local and general coordinate systems in Z direction. Similarly angle of each axis is defined with respect to general coordinate systems of measuring locations at B and C. if V_1, V_2 and $V_3$are the vibrations measured at measuring locations A, B and C respectively. Vibration of the object in X, Y and Z directions can be obtained using the above angles and the equation (6) as follows (DAVID et al., 2009):

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} Cos\theta'_{xx} & Cos\theta'_{xy} & Cos\theta'_{xz} \\ Cos\theta'_{yx} & Cos\theta'_{yy} & Cos\theta'_{yz} \\ Cos\theta'_{zx} & Cos\theta'_{zy} & Cos\theta'_{zz} \end{bmatrix}^{-1} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \text{------------ (8)}$$

7. CONCLUSION

Vibration is one of the important factor that plays a vital role on the performance of cutting tool as well as tool life, surface quality of finished component and power consumption. Hence, it is essential to measure vibration of tool or workpiece. In TCM, contact and non-contact sensors are used for online acquisition of vibration data. Working and setup of contact and non-contact sensors was discussed. From this paper, the following points can be drawn for the discussion:

- Contact sensors are used for measurement of vibration of fixed body like tool holder in turning and work pieces in milling process.
- Vibration of rotating bodies like work pieces in turning, mill cutters and drill bits cannot be measured with contact sensors, because of the fact that the contact sensors cannot be fixed on rotating bodies.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

- Time and frequency domain are more advantageous to identify maximum amplitude of vibration of a rotating body.
- Use of non-contact sensors like Laser Doppler Vibrometers is easy and simple to measure vibration of any rotating/moving body.
- Set up of LDV is easy and very simple when compared with set up of contact sensors.
- Among the methods available for measurement of vibration, LDV promises to be accurate and speedy in operation. Although not many works have been conducted using LDV, hence there is ample scope for this non-contact technique studies.,
- 3 D vibration measurement was introduced by measuring vibration of an object with single LDV at 3 different locations by moving the LDV.

REFERENCES

ABDUL, B. S.; SHIVAKUMAR, R. (1987) Detection of tool flank wear using acoustic signature analysis. **Wear**, v. 115, n. 3, p. 265-272.

AKESSON, H.; SMIRNOVA, T.; CLAESSON, I.; HAKANSSON, L. (2007) On the Development of a Simple and Robust Active Control System for Boring Bar Vibration in Industry. **International Journal of Acoustics and Vibration**, v. 12 , n. 4, p. 139-152.

ALONSO, F. J.; SALGADO, D.R. (2008) Analysis of the structure of vibration signals for tool wear detection. **Mechanical Systems and Signal Processing**. v. 22, n. 3, p. 735-748.

ANDREN, L.; HAKANSSON, L.; BRANDT, A.; CLAESSON, I.; (2004) Identification of dynamic properties of boring bar vibrations in a continuous boring operation. **Mechanical Systems and Signal Processing**, v. 18, n. 4, p. 869–901.

BALAJI, M.; VENKATARAO, K.; MOHANARAO, N.; MURTHY, B. S. N. (2018) Optimization of drilling parameters for drilling of TI-6Al-4V based on surface roughness, flank wear and drill vibration. **Measurement**, v. 114, p. 332-339.

BELL, J. R.; ROTHBERG, S. J. (2000) Rotational vibration measurements using laser Doppler vibrometry: comprehensive theory and practical application. **Journal of Sound and Vibration**, v. 238, n. 4, p. 673-690.

CASTELLINI, P.; SCALISE, L.; REVEL, G. M. (2000) Vibration measurements for diagnosis of structural defects on human teeth. **Measurement**, v. 27, n. 1,p. 29-42

CHANG, F. Y.; RICHARD, J. H. (1989) Acoustic emission true RMS signals used to indicate wear of a high speed ceramic insert. **Journal of Mechanical Working Technology**. v. 20, p. 79-91.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

CHANG, F. X. (2001) An Experimental Study of the Impact of Turning Parameters on Surface Roughness. **Proceedings of the Industrial Engineering Research Conference**. Paper n. 2036, GA.

CHELLADURAI, H.; JAIN, V. K.; VYAS, N. S. (2008) Development of a cutting tool condition monitoring system for high speed turning operation by vibration and strain analysis. **International Journal of Advanced Manufacturing Technology**, v. 37, p. 471–485.

CHERAN, G. L.; JIA-MING, L. (2007) Study on boring and drilling with vibration cutting. **International Journal of Machine Tools and Manufacture**, v. 47, n. 1, p. 133-140.

CHIH-CHERNG, CH.; NUN-MING, L.; KO-TA, CH.; HUA-LUN, CH. (2012) Experimental investigation of tool vibration and surface roughness in the precision end-milling process using the singular spectrum analysis. **International Journal of Advanced Manufacturing Technology**, v. 63, p. 797–815.

DAVID, A. S.; JOHN, S. A. (2006) Metal cutting theory and practice. **Taylor and Francis**, 1st edition, p. 45-69.

DAVID, E. O.; MATTHIAS, S. (2009) Automated robot-based 3D vibration measurement system. **Sound & Vibration**, v. 43, n. 4, p. 12-15.

DIMLA, D. E. SR.; LISTER, P. M. (2000) On-line metal cutting tool condition monitoring.: I: force and vibration analyses. **International Journal of Machine Tools and Manufacture**, v. 40, n. 5, p. 739-768.

DONGKYU, K.; KYIHWAN, P. (2013) Development of the pseudo 3-dimensional laser scanning vibrometer. **20th International Congress on Sound and Vibration (ICSV20)**, Bangkok, Thailand.

DONGKYU, K.; HAJUN, S.; HOSSAM, K.; JONGSUH, L.; SEMYUNG, W.; KYIHWAN, P. (2014) 3-D Vibration Measurement Using a Single Laser Scanning Vibrometer by Moving to Three Different Locations. **IEEE transactions on instrumentation and measurement**, v. 63, n. 8, p. 2028-2033.

DORNFELD, D. A.; KANNATEY, A. E. (1980) Acoustic emission during orthogonal metal cutting. **International Journal of Mechanical Sciences**. V. 22, p. 285-296.

EWINS, D. J. (1984) Modal Testing: Theory and Practice. **Research Studies Press**- John Wiley.

GHANI, A. K.; CHOUDHURY, I. A.; HUSNI. (2002) Study of tool life, surface roughness and vibration in machining nodular cast iron with ceramic tool. **Journal of Materials Processing Technology**. v. 127, n. 1, p. 17-25.

INMAN, D. J. (2001) Engineering Vibration. **Prentice-Hall**, 2nd edition, p. 258-269.

KOUROSH, T.; PER, G. (2008) Measurement of milling tool vibrations during cutting using laser vibrometry. **International Journal of Machine Tools and Manufacture**, v. 48, n. 3-4, p. 380-387.

LUKE, H. H.; JOSEPH, C. C. (2001) A Multiple Regression Model to Predict In-Process Surface Roughness in Turning Operation Via Accelerometer. **Journal of Industrial Technology**, v. 17, n. 2, p. 2-7.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

MIGUÉLEZ, M. H.; RUBIO, L.; LOYA, J. A.; FERNÁNDEZ, S. J. (2010) Improvement of chatter stability in boring operations with passive vibration absorbers. **International Journal of Mechanical Sciences**, v. 52, n. 10, p. 1376-1384.

NGOI, B. K. A.; VENKATAKRISHNAN, K. (2000) An Acousto-Optic Vibrometer for Measurement of Vibration in Ultra-Precision Machine Tools. **The International Journal of Advanced Manufacturing Technology**, v. 16, n. 11, p. 830-834.

OSTASEVICIUS, V.; GAIDYS, R.; RIMKEVICIENE, J.; DAUKSEVICIUS, R. (2010) An approach based on tool mode control for surface roughness reduction in high-frequency vibration cutting. **Journal of Sound and Vibration**, v. 329, n. 23, p. 4866-4879.

PRASAD, B. S.; SARCAR, M. M. M.; SATISH, B. B. (2010) Development of a system for monitoring tool condition using acousto-optic emission signal in face turning—an experimental approach. **International Journal of Advanced Manufacturing Technology**. v. 51, p. 57–67.

RAHIM, I. A.; MISKAM, M. A.; SIDEK, O.; ZAHARUDIN, S. A.; MOHD, S. K. K. (2009) Development of a vibration measuring unit using a microelectromechanical system accelerometer for machine condition monitoring. **European Journal of Scientific Research**, v. 35, n. 1, p. 150–158.

ROBERTO, M.; LUCIANO, P.; GIANLUCA, R. (2000) Vibration measurements of tools inside fluids by laser Doppler techniques: uncertainty analysis. **Measurement.,** v. 27, n. 2, p. 111–120.

ROBERTO, T.; MICHELETTI, G. F. (1989) Tool Wear Monitoring Through Acoustic Emission. **CIRP Annals - Manufacturing Technology**. v. 38, n. 1, p. 99-102.

SADETTIN, O.; ALI, O.; NECIP, C.; ERSAN, A. (2007) Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness. **NDT & E International**, v. 40, n. 2, p. 121-126.

SALGADO, D. R.; ALONSO, F. J.; CAMBERO, I.; MARCELO, A. (2009) In-process surface roughness prediction system using cutting vibrations in turning. **International Journal of Advanced Manufacturing Technology**. v. 43, p. 40–51.

SIVASAKTHIVEL, P. S.;VELMURUGAN, V.; SUDHAKARAN, R. (2011) Prediction of vibration amplitude from machining parameters by response surface methodology in end milling. **International Journal of Advanced Manufacturing Technology**, v. 53, p. 453–461.

THOMAS, M.; BEAUCHAMP, Y. (2003) Statistical investigation of modal parameters of cutting tools in dry turning. **International Journal of Machine Tools and Manufacture**, v. 43, n. 11, p. 1093-1106.

TOBIAS, S. A. (1965) **Machine-Tool Vibration**. Blackie and Sons Ltd, Scotland. p. 132-135.

VENKATARAO, K.; MURTHY, P. B. G. S. N. (2016) Modeling and optimization of tool vibration and surface roughness in boring of steel using RSM, ANN and SVM. **Journal of Intelligent Manufacturing,** DOI: 10.1007/s10845-016-1197-y.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License

http://www.ijmp.jor.br v. 9, n. 4, October - December 2018
ISSN: 2236-269X
DOI: 10.14807/ijmp.v9i4.801

VENKATARAO, K. (2014) **Tool condition monitoring by analyzing surface roughness, workpiece vibration and volume of metal removed in boring of steel**. Thesis (Ph D in Machine design and Manufacturing). JNTUK: Kakinada.

VENKATARAO, K.; MURTHY, B. S. N.; MOHANRAO, N. (2013) Cutting tool condition monitoring by analyzing surface roughness, work piece vibration and volume of metal removed for AISI 1040 steel in boring. **Measurement**, v. 46, p. 4075–4084.

VENKATARAO, K.; MURTHY, B. S. N.; MOHANRAO, N. (2014) Prediction of cutting tool wear, surface roughness and vibration of work piece in boring of AISI 316 steel with artificial neural Network. **Measurement**, v. 51, p. 63–70.

WANG, H.; TO, S.; CHAN, C. Y.; (2013) Investigation on the influence of tool-tip vibration on surface roughness and its representative measurement in ultra-precision diamond turning. **International Journal of Machine Tools and Manufacture**, v. 69, p. 20-29.

XIAO. M.; SATO, K.; KARUBE, S.; SOUTOME, T. (2003) The effect of tool nose radius in ultrasonic vibration cutting of hard metal. **International Journal of Machine Tools and Manufacture**, v. 43, n. 13, p. 1375–1382.

XIAOLI, LI. (2002) A brief review: Acoustic emission methods for tool wear monitoring during turning. **International Journal of Machine Tools and Manufacture**, v. 42, n. 2, p. 157-165.

ZAHIA, H.; AHMED, B.; MOHAMED, A. Y.; TAREK, M.; JEAN-FRANÇOIS, R. (2013) On the prediction of surface roughness in the hard turning based on cutting parameters and tool vibrations. **Measurement**, v. 46,n.5, p. 1671–1681.

[http://creativecommons.org/licenses/by/3.0/us/]
Licensed under a Creative Commons Attribution 3.0 United States License