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IMPROVING MACHINING PERFORMANCE AGAINST REGENERATIVE TOOL CHATTER THROUGH ADAPTIVE NORMAL PRESSURE AT THE TOOL CLAMPING INTERFACE

Chatter in machining process is one of the common failures of a production line. For a cantilever tool, such as a boring bar, the rule of thumb requires the overhang length of the tool to be less than 4 times the diameter. The reason is because longer overhang will induce severe tool vibration in the form of chatter during machining. When a longer overhang than 4 times diameter is necessary for performing special machining operations, damping methods are needed to suppress tool chatter. One of the methods is the constrained layer damping method. Materials, such viscoelastic material, are applied in the vibration node regions of the structure to absorb the concentrated vibration strain energy and transform the mechanical energy to heat. With a cantilever tool clamped in a tool holder, the clamping interface is usually the vibration node region. The friction in the joint interface with low normal pressure became another source of damping and can be used for tool chatter suppression in mechanical structures. Joint interfaces are well known to possess normal pressure dependent stiffness and damping. The normal pressure's effect on the structures frequency response function had been observed by H. Åkesson [1] et al, and L.Mi [2] et al. However, the direct effect of the joint interface normal pressure on machining process stability hasn't been investigated. In this paper, a cantilever tool with 6,5 overhang length to diameter ratio is investigated. The direct effect of the tool clamping interface's normal pressure on the machining process stability is studied. Three different levels of clamping normal pressure are tested with an internal turning process. The machining results indicate another adaptable solution on shop floor for suppressing tool chatter.

1. INTRODUCTION

The regenerative tool chatter during a machining operation is still a major limit for process performance [3],[4]. In machining operation such as boring, drilling, turning and milling, the tooling systems are exposed to unstable vibrations in the form of chatter.

Chatter theory addressed the importance of the cross transfer function of the tool and workpiece, especially the real negative part of the cross transfer function [5],[6],[7]. The relationship between the spindle speed and chatter frequency decides the number of cycles that excite the vibration. Through adjusting the spindle speed, the machining process can be maintained stable while performing the operation at the spindle speeds which are optimized

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for the stability limit [6]. Fig. 1 is an example which shows the relation between the spindle rotation speed and the stability limit, developed by J. Gurney and Tobias [6].

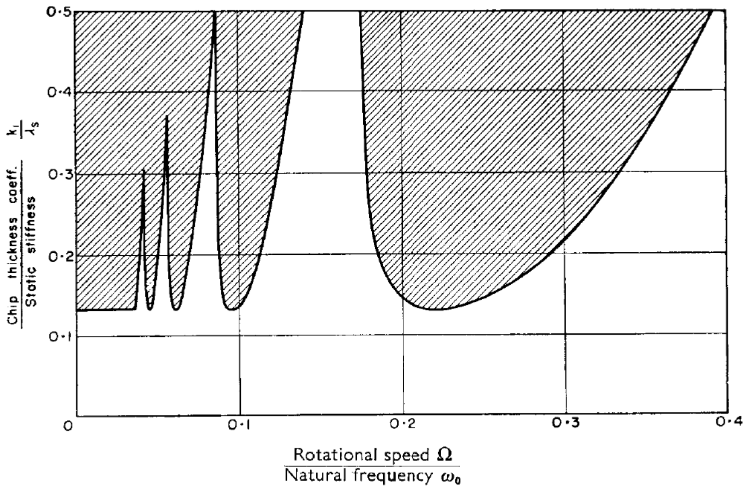

Fig. 1. An example of the stability lobes diagram, the shaded area represents the chip thickness coefficient which results in un-stable machining condition, and the rotation speed of the spindle affects the stability limit [6] (The chip thickness coefficient is illustrated as cutting force coefficient in other literatures [8])

The equation for calculating the stability limit expressed as $a_{p,lim}$ (depth of cut limit) is shown as equation [9]:

$$a_{p,lim} = -\frac{1}{2 * k_c * Re\ G\ \ w \quad * \mu}$$

Where: k_c [10] is the specific cutting force, μ is the overlapping factor between the consequent tool paths and $Re[G(w)]$ is the negative real part of the transfer function of either the workpiece or the tool. The specific cutting force k_c is dependent on the feed rate, rake face angle, nose radius, and cutting speed [11] etc. In the internal turning process, the cutting depth stability limit will be primarily determined by the transfer function oriented in the direction of cutting speed [12].

In order to overcome the weakness of tooling system's performance against chatter, process parameters are usually sub-optimized and common actions include:

- change the spindle speed towards a stable region [13],
- reduce the cutting speed to incorporate more process damping [14],
- shorten the tool overhang length [15],
- reduce the nose radius of the inserts [9],
- increase the rake face angle of the cutting edge [16],
- reduce the depth of cut [9],
- increase the feed rate to minimize the tool path overlap [9].

When a cantilever tool is used for machining, the rule of thumb for avoiding tool chatter usually requires the overhang length to be less than 4 times the diameter of the tool

[3]. If a longer overhang is needed for performing specific machining operations, damping solutions must be available to ensure the machining process stability.

There are two main categories of damping methods named active damping method and passive damping method [17] respectively. The active damping method utilizes the piezo-electric technique and applies a compensating force at the exact chatter frequency and suppresses the chatter vibration [18]. The passive damping method makes use of high damping material and applies the material in two different ways namely:

- tuned mass damper [19],
- constrained layer damping [17].

Tuned mass dampers transfers the vibration energy to extra features on the structure and thus maintain the machining process stable [19]. Constrained layer damping application applies the high damping material (such as viscoelastic material) in the regions where vibration strain energy concentrates [17]. When a structure is vibrating at a certain frequency, the anti-node regions have the highest vibration amplitude, and the node regions have the highest vibration strain energy [20].

For cantilever tools, the vibration strain energy usually concentrates at the clamping end of the tool while the tool is oscillating at the 1^{st} natural frequency. The normal pressure dependent stiffness and damping of the joint interfaces [21-24] make the clamping interface a possible source for vibration damping. The interface with fasteners in machine structures generally loses partially the static stiffness in comparison to a monolithic structure [22]. The benefit of applying such interfaces in machine structures is the damping effect in the contact area under tangential loading [23].

The joint interface property's normal pressure dependency is well-known for researchers. M. Rahman [25] was the first to document the clamping condition of a workpiece affects machining process stability in 1985. The effect of the joint interface's normal pressure on the machining tool's frequency response function had been observed by H. Åkesson [1] and L. Mi [2] et al. However, the direct effect of the joint's pre load on a machining tool's capability of performing stable machining process had not been fully investigated.

The hypothesis of this paper is that the machining tool's clamping pre-load condition has a vital effect on the machining process stability. An adaptable approach of adjusting tool's clamping conditions for suppressing regenerative tool chatter in an internal turning machine is presented and investigated with a boring bar fixed at 6,5 times diameter overhang length. The experiments results show that the machining process performance against tool chatter is substantially improved while reducing the tool's clamping pre-load and increasing friction damping in the interface.

2. EXPERIMENT SETUP

2.1. TURNING PROCESS SET UP

An internal turning process is chosen as the platform to conduct the study. A turning tool with 25mm diameter and free hanging length 163mm (length to diameter ratio is 6,5) is clamped with a hydro-fix clamper in a standard VDI tool holder. The tool holder is then rigidly fixed on a turret (a revolver which functions as a tool magazine).

Nose radius of the inserts is 0.8mm to ensure that the overlapping factor of the machining process is big enough to excite the chatter vibration. The feed rate is fixed at 0.2mm/rev, and depth of cut (ap) is fixed at 1mm. The depth of cut is chosen for controlling the ratio between the dynamic force coming from the previous surface wavelets and the static cutting force.

During the experiment, the preparation of surface cleaning is not performed for each of the operation, although the machining process has its own tendency towards following the previous surface wavelets. Since most of the excitation energy for chatter is regenerative, the percentage of the excitation energy caused by the previous cut surface wavelets is small in comparison to the regenerative amount of energy. This is determined by the overlapping factor μ [4].

The machining experiments were based on the fixed cutting speed, which means the spindle speed will depend on the internal diameter of the workpiece. This is to eliminate the effect of cutting speed on specific cutting resistance during the process. At the beginning of the experiments, the initial spindle speed will be chosen to fix the cutting speed to be 140m/min as recommended by the supplier of the inserts. During the machining process, the spindle speed was increased with 5% as a step until 25% increase. By doing that, 6 different spindle speeds were used sequentially to test the machining process stability on a spindle speed range.

Hydro-fix fixture is provided by Spirex Tools AB [26] and the contact surface preload is changed through changing the clamping torque on the screw as shown in Fig. 2. The selection of the minimum clamping torque is based on the criterion that the tool insert will keep its initial position during the machining operation without moving. As the depth of cut is fixed at 1mm, feed rate is fixed at 0,2mm/rev, and initial cutting speed is fixed at 140m/min, the minimum clamping torque is chosen at 3Nm which ensures that the tool will not rotate while loaded with static load from the machining operation. A torque wrench is used to control and measure the preload. Three levels of clamping torque were used as 3Nm, 6Nm, and 9Nm. The machining process parameters are summarized below.

Table 1. Summary of the machining process parameters

	internal diameter (mm)	spindle speed (rpm)	clamping torque (Nm)
Run 1	46	968-920	3
Run 2	48	926-930	6
Run 3	50	890-893	9
Run 4	52	856-859	3
Run 5	54	824-827	6
Run 6	56	795-798	9
Run 7	58	768-771	3
Run 8	60	741-745	6
Run 9	62	717-721	9

Workpiece is a steel (SS2541, ISO 4340) slot with outer diameter 120mm, inner diameter 40mm, and length 170mm. The geometry of the workpiece was maintained in a range which ensures the stiffness of the workpiece is higher than that of the internal turning tool, thus eliminate the possibility of chatter vibration from the workpiece.

2.2. IMPACT TESTING AND MACHINING PROCESS ACCELERATION MEASUREMENT SET UP

An impact hammer (Dytran ZIEGLER IXYS SN 9117) with an Aluminum tip is used to excite the tool from the free hanging end of the tool. Three accelerometers (Dytran model 3225F) were waxed on the tool shank as shown in Fig. 2. Two sets of FRFs (frequency response functions) were measured with accelerance in the cutting speed direction and radial direction of the tool respectively.

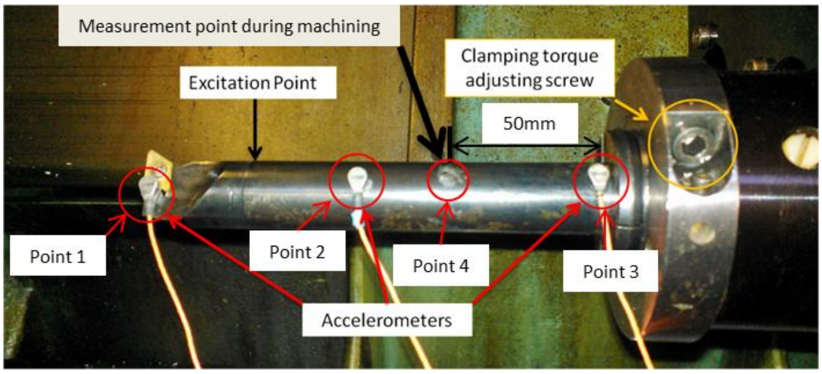

Fig. 2. Impact testing set up

2.3. MACHINING PROCESS MEASUREMENT

During the machining process, two accelerometers were mounted on the tool for vibration measurement. One of the accelerometer is measuring the cutting speed direction (Y direction of the machine’s coordinate system) tool vibrating signal, and the other one measures the radial direction (X direction of the machine’s coordinate system) tool vibrating signal. The two accelerometers were waxed with a distance of 50mm to the tools clamping end (Point 4 as shown in Figure 2).

2.4. SURFACE MEASUREMENT

The surface roughness is measured by a MITOTOYO SJ301 surface roughness measuring probe. Travel length of the probe is approximately 5mm. One roughness measurement on random positions is done to indicate the surface finish attached with a picture taken from each of the machined surface.

3. RESULTS

3.1. IMPACT TESTING RESULTS

The impact testing results on Point 1 with three different levels of clamping torques in two directions (X, and Y) are summarized in Fig. 3:

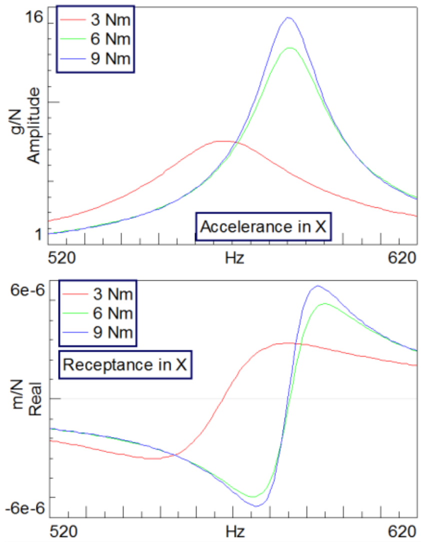

Fig. 3. Synthesized impact testing result measured on Point 1, acceleration in X and Y directions on the top, real part of receptance in X and Y directions in the bottom

3.2. SURFACE FINISH AND ACCELERATION MEASUREMENT DURING MACHINING

The model analysis result on Point 1 is summarized in Table 2.

Table 2. Summary of the model analysis results

	Mode X			
clamping torque (Nm)	frequency (Hz)	dynamic stiffness at the mode frequency (N/µm)	damping ratio %	maximum amplitude (g)
3	568	0,171	3,2	7,56
6	585	0,102	1,7	13.47
9	585	0,089	1,4	15,35
	Mode Y			
clamping torque (Nm)	frequency (Hz)	dynamic stiffness at the mode frequency (N/µm)	damping ratio %	maximum amplitude (g)
3	570	0,163	2,34	8,01
6	576	0,139	2,16	9,58
9	578	0,130	2,04	10,35

The surface finish results are summarized in Fig. 4:

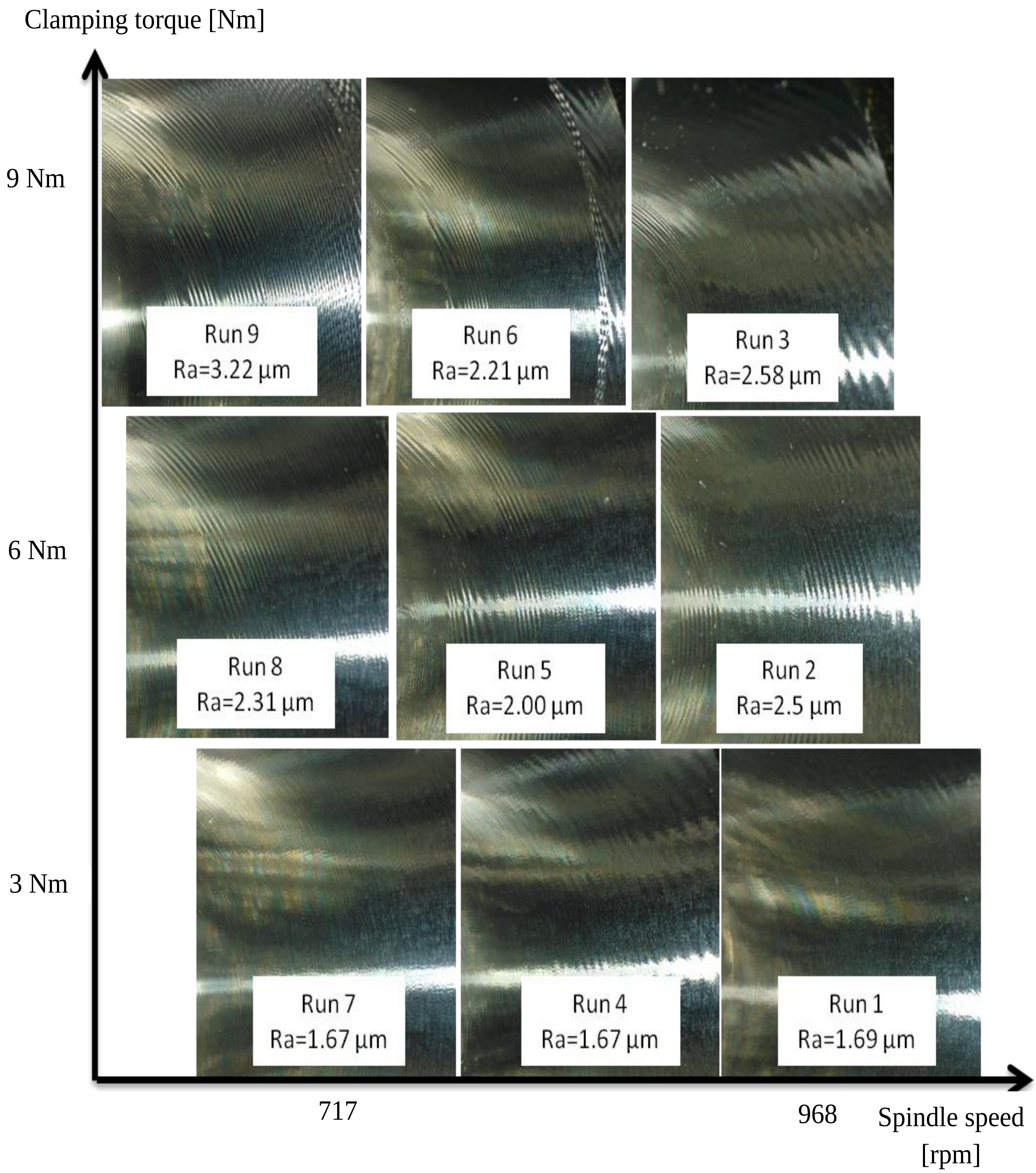

Fig. 4. Surface finish results with pictures and Ra value

The acceleration measurement result on Point 4 as shown in Fig. 2 during the machining process in both X and Y directions are summarized in Fig. 5 and Fig. 6:

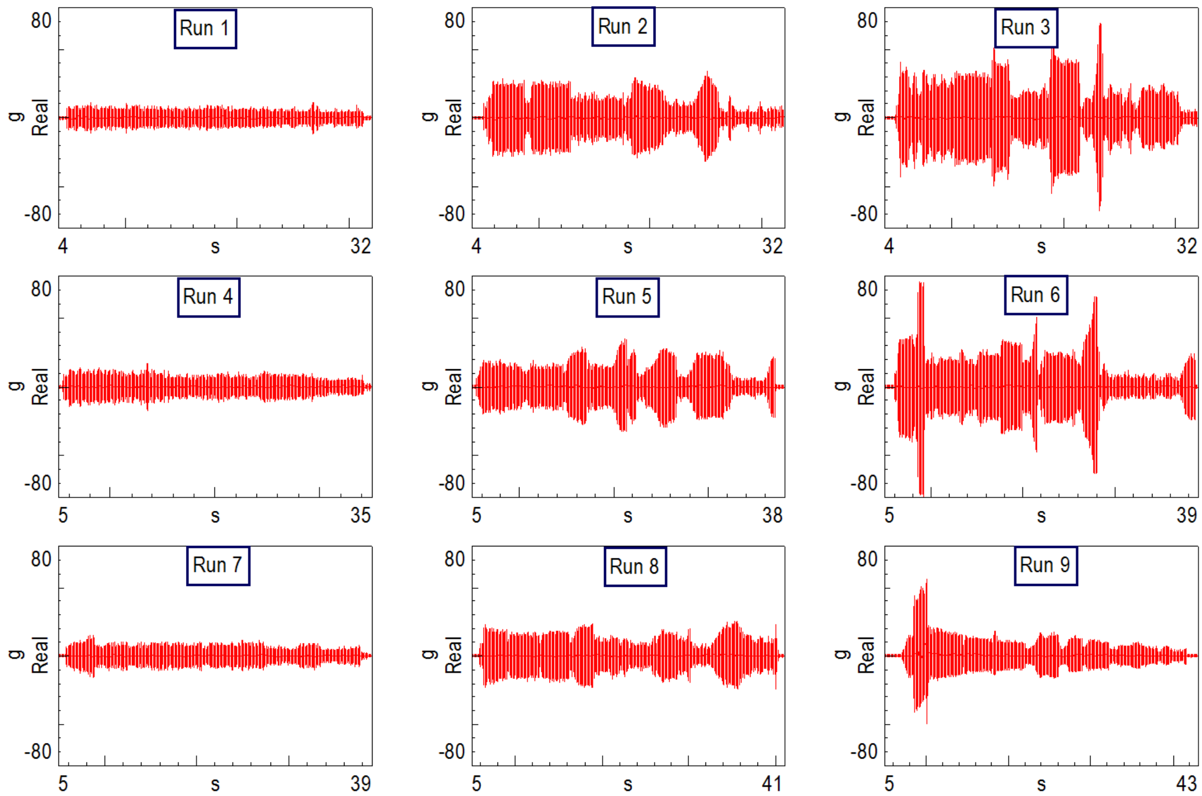

Fig. 5. Acceleration measurement on Point 4 during machining in X direction

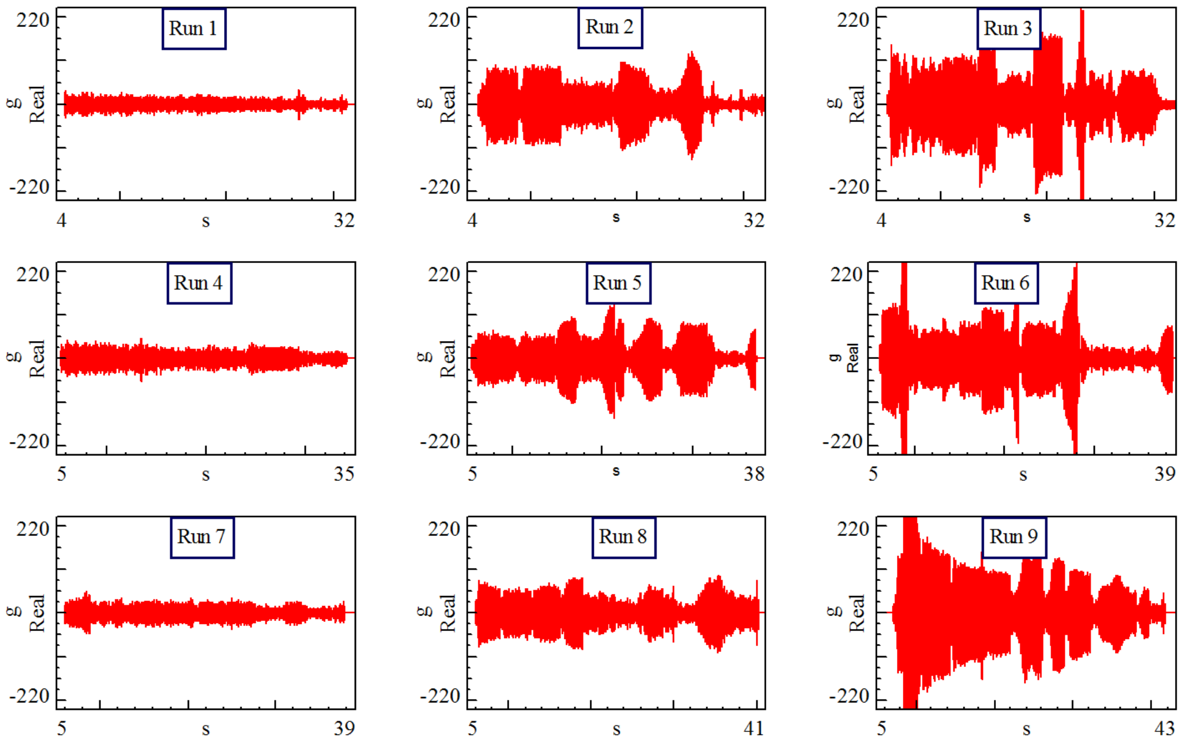

Fig. 6. Acceleration measurement during machining in Y direction

The power spectrum density of measured acceleration data in X and Y direction during machining process is summarized in Fig. 7 and Fig. 8:

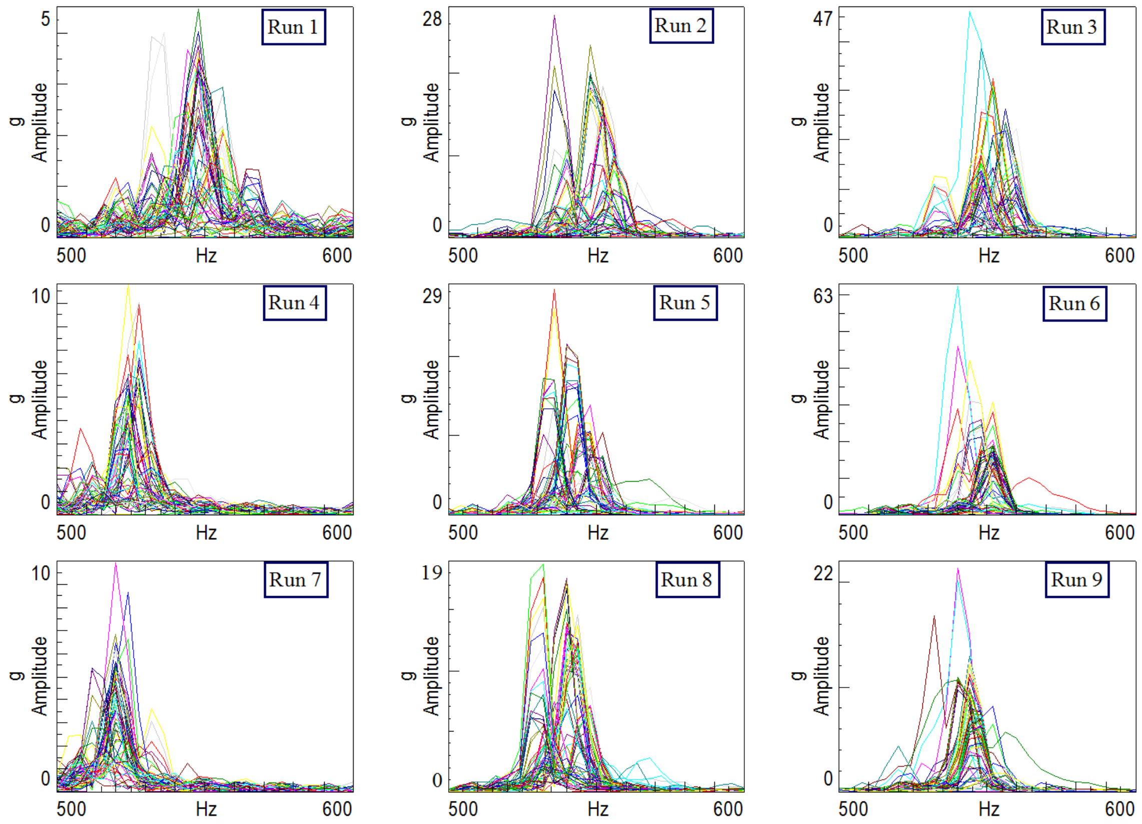

Fig. 7. Power spectrum density of measured acceleration data in X direction during the machining processes

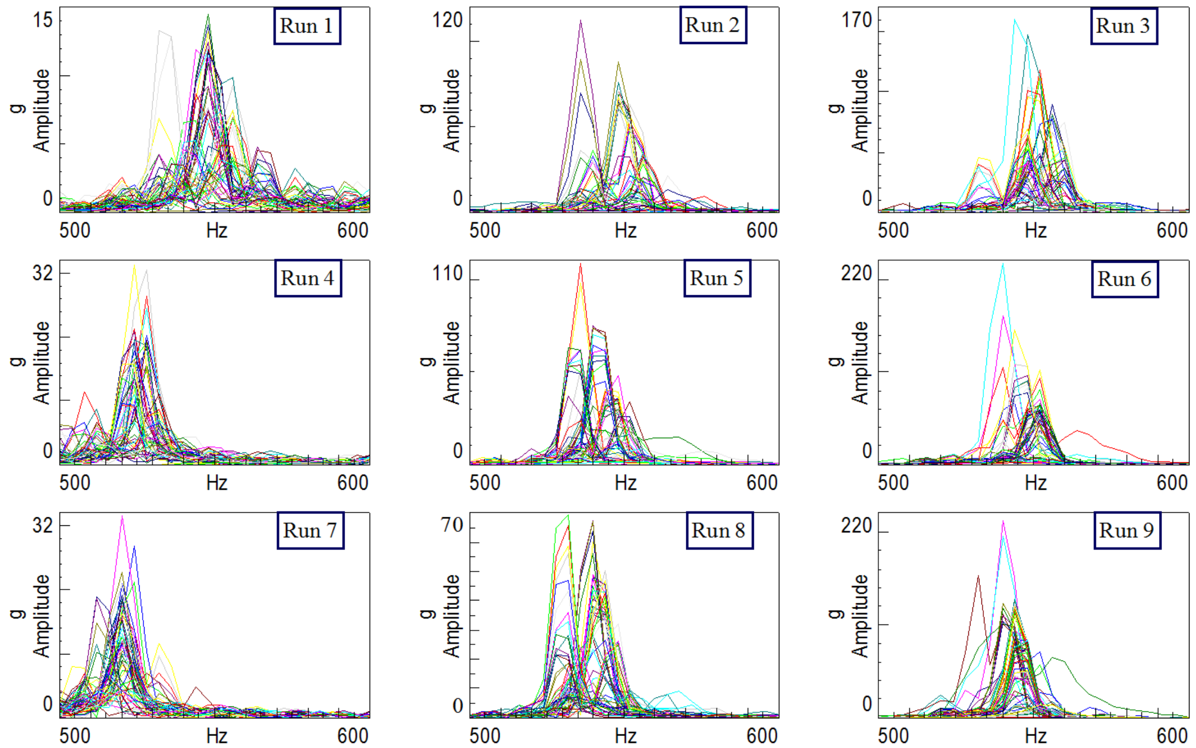

Fig. 8. Power spectrum density of measured acceleration data in Y direction during the machining processes

4. DISCUSSION OF RESULTS

4.1. SUMMARY OF THE IMPACT TESTING RESULT

The impact testing results in Fig. 3 show that, while changing the clamping torque, the FRFs measured on the same point of the tool shank with force input at the same position is changing. While the torque is higher, the clamping pressure of the interface between the hydro-fix and the tool is higher. According to Ito [22] higher contact pressure at the interface will increase the static stiffness of the joint and decrease the damping capacity of the joint.

The measured receptance data in the lower part of Fig. 3 shows that, in the frequency range where the chatter frequency lies, 3Nm clamping torque has the highest minimum receptance. According to equation (chapter 1), the higher is the minimum receptance value, the higher is the critical stability limit [27]. With the higher level of the critical stability limit, the machining process is more robust while suppressing chatter.

The summary of model analysis results in Table 2 shows that the dynamic stiffness at the mode frequency is highest in both X and Y directions with 3Nm clamping torque. The loss in dynamic stiffness while adding 3Nm torque from 3Nm to 6Nm clamping torque, is bigger than the loss in dynamic stiffness while adding 3Nm torque from 6Nm to 9Nm in both X and Y direction. This is due to the non-linear friction damping effect in the clamping interface between the tool and the hydro-fix fixture. While maintaining the excitation force amplitude the same, the interface is under seized condition when the clamping torque exceeds 6Nm. When the clamping torque is 3Nm, the excitation force could have exceed the limit for stick-slip phenomenon [28]. The stick-slip phenomenon is related to the energy transmission in the contacting interface. Although the friction damping from stick-slip phenomenon is obtained while clamping torque is 3Nm, the tool is not rotating or moving during the machining process.

Analysis result shows that, the mode shape is linear with the three points while moving with the same frequency and same direction. Therefore, the machining process acceleration measurement on the points that are 50mm away from the tools clamping end can be linearly transformed to represent the insert movement at the free end of the tool.

4.2. MACHINING PROCESS MEASUREMENT RESULT

A summary of the experiment results is shown in Table 3.

The maximum amplitude of vibration in Run 4 and Run 7 is approximately 50% higher than that measured in Run 1 in both X and Y directions. The reason could be because the Run 4 is affected by the previous surface wavelets from Run 3 and Run 7 is affected by the previous surface wavelets from Run 6. The shift in vibration frequency shown in Fig. 7 and Fig. 8 between Run 1 to Run 4 and between Run 4 to Run 7 is determined by spindle speed and the excitation frequency produced by the previous wavelets [7]. The intrinsic reason for the frequency shift among Run 1, Run 4 and Run 7 is though not fully explored.

Table 3. Summary of the machining results with additional 1st X and Y mode frequency data

	clamping torque	1st mode frequency X	Chatter frequency X	1st mode frequency Y	Chatter frequency Y	Maximum **acceleration** amplitude in X	Maximum **acceleration** amplitude in Y	Maximum power spectrum density value in X	Maximum power spectrum density value in Y	Surface rougness Ra
	(Nm)	(Hz)	(Hz)	(Hz)	(Hz)	(g)	(g)	(g)	(g)	(μm)
Run 1	3	568	534-549	570	534-549	11	35	4	14	1,69
Run 2	6	585	534-547	576	534-547	34	130	27	113	2,50
Run 3	9	585	545-556	578	545-556	69	250	46	160	2,58
Run 4	3	568	508-528	570	508-528	17	54	10	32	1,67
Run 5	6	585	532-552	576	532-552	35	140	28	109	2,00
Run 6	9	585	540-552	578	540-552	76	280	63	220	2,21
Run 7	3	568	512-524	570	512-524	15	50	10	32	1,67
Run 8	6	585	527-547	576	527-547	25	90	19	70	2,31
Run 9	9	585	532-551	578	532-551	56	300	21	213	3,22

The measured acceleration amplitude in X and Y directions shown in Fig. 5 and Fig. 6 reveals that the vibration during operations is dominated by the movement in Y direction, which is the same as the cutting speed direction, although the response in X direction is higher under the same excitation as shown in Fig. 3. This observation is in line with Andren et al [29] where they claimed the vibration in a boring process is mainly concentrated in the cutting speed direction.

Results shown in Fig. 7 and Fig. 8 reveal that the chatter frequency is related to the frequency range where the receptance value is negative. This observation agrees with the theory of tool chatter in machining provided by Tobias et al [7]. The chatter frequencies for both X and Y directions are in the same range, and a higher amplitude of vibration is measured in Y direction. The chatter comes from direction Y. Andren et al [29] discussed that the chatter is mostly from the direction of cutting speed in a boring operation.

There are two main criteria for machining process chatter. S.Y. Tsai et al [30] used the criterion of the maximum value of the power spectral density function. Li et al [31] proposed the criterion of the ratio between the predicted maximum dynamic cutting force to the predicted maximum static cutting force. The power spectrum density graphs (Fig. 7 and Fig. 8) show that the vibration energy is concentrated to a certain frequency band for all of the machining operations. It is difficult to conclude which operations are under chatter condition. It is clear that with reducing the clamping torque, the maximum value of the power spectrum density function will decrease.

It is clear that the vibration during the machining process is because of tool chatter instead of forced vibration as the vibration frequency is above 500Hz and spindle rotation frequency is less than 20Hz.

The spindle speed could have been important to define the stability limit of the machining process. In order to overcome the effects from the spindle speed changes, the experiments were conducted based on five different spindle speeds for each of the cutting operation. The repeatable phenomenon of higher vibration amplitude with higher clamping torque on the tool is easy to observe.

The extra dynamic stiffness induced by releasing the clamping torque might also be because of the change of the hydraulic oil's property in the Hydro-fix fixture. Extra effort is needed to identify the change of the contact interface's property between the tool and the fixture, and clarify the reason for better dynamic behavior of the tools while reducing the clamping torque. The authors hold the opinion that the improvement is because of the pressure change at the interface between the tool and the hydro-fix clamping fixture.

5. CONCLUSION

From the machining results shown in Fig. 4, Fig. 5 and Fig. 6, a conclusion can be made that the 3Nm clamping torque is most beneficial for obtaining a stable machining process while higher clamping torque will induce more vibration instability in the machining process.

A conclusion can be made that clamping pre-load condition has a vital effect on the machining process stability while the process is exposed to chatter. A new approach of improving machining process performance of a cantilever tool against regenerative tool chatter is provided through adaptive normal pressure at the tool clamping interface.

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