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vibrations, milling,
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EXPERIMENTAL ANALYSIS OF A MACHINING SYSTEM WITH ADAPTIVE DYNAMIC STIFFNESS

A main consideration in the operation of machine tools is vibrations occurring during the cutting process. Whether they are forced vibrations or self-excited ones, they have pronounced effects on surface quality, tool life and material removal rate. This work is an experimental study of interactions between natural characteristics, control parameters and process parameters of a machining system designed with adaptive dynamic stiffness. In order to comprehend these interactions, the effect of changes in dynamic stiffness on the system's response is examined. The system under study consists of an end-milling tool, a steel workpiece and a work holding device with controllable stiffness. Natural dynamic characteristics of the system components are determined through modal impact testing. Then the behaviour of the whole machining system is examined under both high and low cutting speed conditions by analysing vibration levels using acceleration signals acquired through a tri-axial sensor mounted on the workpiece. Cutting is performed in both directions of the horizontal plane of a CNC milling machine. In both cases the results are presented for two extremes of stiffness and damping in the work holding device. The effect of control parameters on the system's natural characteristics could be identified together with a relation between these parameters and the system's response in high and low cutting speed conditions. The high-damping configuration reduces the vibration amplitudes significantly, while the increase of pre-stress has a different effect depending on the cutting conditions.

1. INTRODUCTION

In machining operations, vibrations that occur during the cutting process are a main consideration since they can have detrimental effect on surface quality, tool wear, machine health etc. [1] Therefore, a great deal of work has been carried out in order to understand the nature of vibrations [2] and find ways to minimize them together with studying the structural characteristics of machines [3] . Such efforts have addressed the problem from several different perspectives; from a process point of view [4], from machine tools' structural dynamic behaviour point of view, or through passive or active vibration control [5],[6],[7]. The importance of the interactions between these three areas has been highlighted especially in terms of the effect of vibrations on tool wear [8],[9].

This research is reporting the developments of a work holding device with adaptive dynamic behaviour, where the joint interface is used as a source of designed-in damping in

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order to improve dynamic stiffness. From the perspective of control through machining systems' structural characteristics, it is an experimental investigation of how a machining system's control parameters, natural characteristics and process parameters interact and how these interactions are reflected in the response of the system to machining excitations, i.e. the dynamic cutting force during machining. The major control parameter in this examination is the pre-stress which affects primarily the static stiffness of the work holding device and the level of interface damping between two components of the work holding device. The increased damping is introduced by the application of viscoelastic material (VEMs) whose behaviour is described by the complex modulus model [10]. The process parameters were selected in order to examine the system's behaviour with two cutting speed conditions.

2. DESCRIPTION OF THE SYSTEM UNDER STUDY

The system under study consists of an end milling tool, a steel workpiece and a work holding device, bolted on the machine table. The workpiece is bolted on an intermediate plate, which is then bolted on the work holding device. The work holding device, made of aluminium alloy, consists of two components, which create an inner interface and is bolted on the machine table. Between the contacting surfaces of the abovementioned components, VEM layers are applied to create the second designed-in damping configuration.

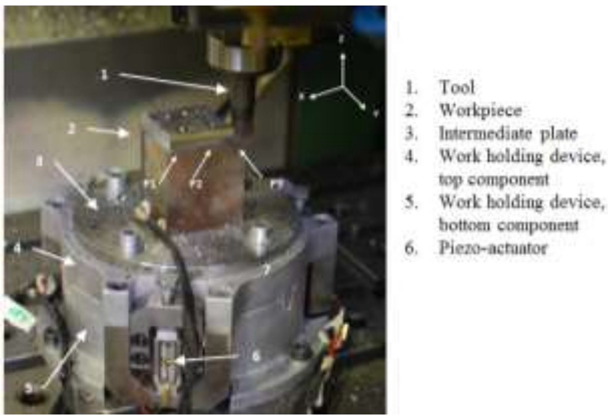

Fig. 1. The experimental setup during machining operation

Controlling the supplied voltage on the 3 piezo-actuators that are placed on the side of the device as seen in Fig. 1 allows the alteration of pre-stress between the two parts of the device and therefore the alteration of its stiffness. An increase in the supplied voltage to the actuators will pull the two components of the device towards each other, increasing the pre-stress between them. The examination of the system in carried out between two extremes of pre-stress, thus 2 extremes of stiffness. In total, four configurations of the system are investigated. In all tests, data were collected by an appropriate data acquisition device and analysed in LMS. Test Lab software platform.

3. MODAL TESTING OF THE SYSTEM UNDER STUDY

The system was analysed with experimental modal analysis in order to identify its natural characteristics and how these are affected by the different configurations of damping and pre-stress. The source of excitation is an impact hammer, while 3 accelerometers were placed on the workpiece in order to acquire the natural characteristics of the system. Tests were conducted for both directions of the XY plane, with Z being the cutting tool axis. The frequency range examined is up to 4096Hz. Table 1 exhibits the static stiffness estimates of the system in the abovementioned four configurations. Fig. 2 shows the acceleration FRFs from the modal tests conducted for point 1 of the workpiece and Fig. 3 shows the acceleration FRFs for all 3 points in the high pre-stress configuration with the VEM layer applied. The effect of VEM layers can be observed in Fig. 2, where their application causes a decrease of amplitudes in most of the modal frequencies, while the effect of pre-stress is more obvious in the VEM-free configuration, in both amplitudes and the frequency values of the FRFs.

Table 1. Change in Static Stiffness between the 4 configurations on X and Y direction

-	X direction		Y direction	
	Low pre-stress (N/mm)	High pre-stress (N/mm)	Low pre-stress (N/mm)	High pre-stress (N/mm)
Without VEM	43360	51587	62273	81794
With VEM	40708	42152	57448	66920

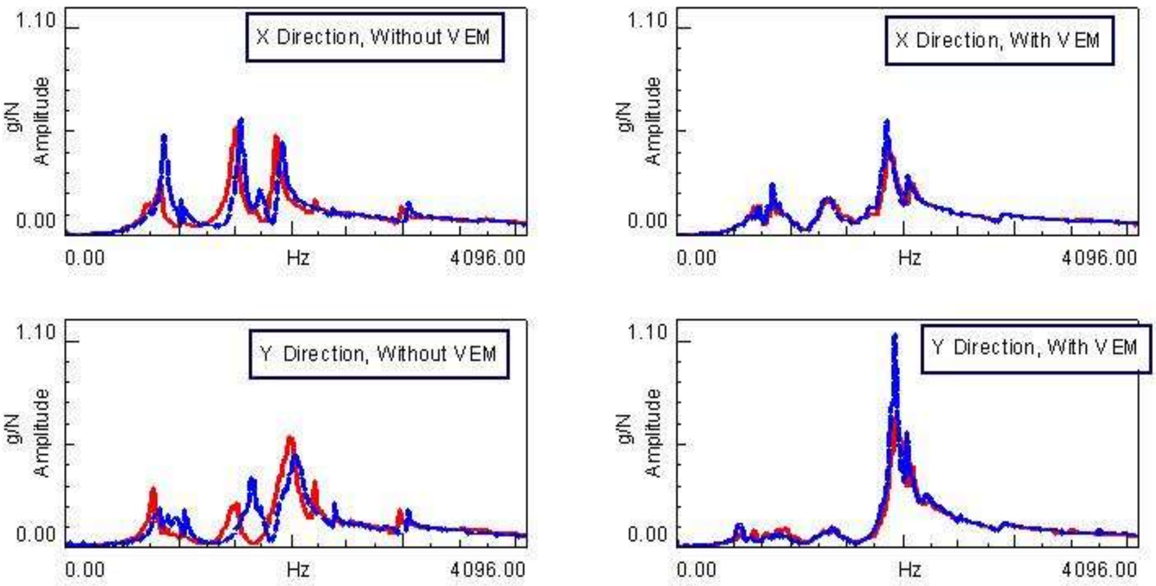

Fig. 2. Comparison of acceleration FRFs for point 1 on the workpiece, red solid lines represent low pre-stress, dashed blue lines represent high pre-stress

The increase in static stiffness with the increase of pre-stress is evident and especially in the case of the VEM-free configuration is much higher compared to the configuration with VEM layers. This can be attributed to the fact that in the VEM configuration, the increased pre-stress is partly transformed into compression of the flexible VEM layers, thus reducing the effect of increased pre-stress on the static stiffness of the system. Besides, in the case of the VEM-free configuration the increased pre-stress leads to an increase of metal-to-metal contact and this is known to cause increased contact stiffness and decreased damping [11]. Regarding the application of the VEM layers, this causes a reduction in static stiffness of the system, which was expected due to the flexible nature of this material.

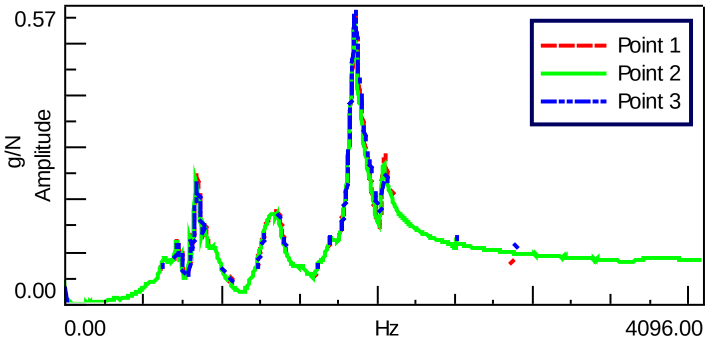

Fig. 3. Acceleration FRFs for points 1, 2, 3 on the workpiece, with VEM, high pre-stress configuration

An examination of the values in Tables 2 and 3 show that in the high pre-stress configuration, the increase in static stiffness observed, is consistent with an expected upward shift of the modal frequencies. Along with the static stiffness, the examination of dynamic stiffness is important especially when the effect of VEM layers is examined. Increased dynamic stiffness indicates that the system vibrates less with the application of the

Table 2. Dynamic stiffness and damping ratio, X direction, Low pre-stress configuration

-	Without VEM			With VEM		
Mode No.	Frequency (Hz)	Damping ratio (ζ)	Dyn. stiffness (N/mm)	Frequency (Hz)	Damping ratio (ζ)	Dyn. stiffness (N/mm)
1	347	4,2 %	7034	340	7,7 %	26885
2	750	4,2 %	12831	716	6,1 %	20817
3	836	2,9 %	11873	838	4,0 %	15279
4	1018	2,1 %	58648	960	3,3 %	33590
5	1508	2,1 %	17499	1337	6,8 %	43545
6	1685	2,6 %	29091	1867	2,3 %	33425
7	1870	1,4 %	115648	2070	1,1 %	85938
8	2211	0,9 %	119832	2511	0,2 %	256723
9	2983	0,6 %	265920	2867	1,5 %	339884

Table 3. Dynamic stiffness and damping ratio, X direction, High pre-stress configuration

-	Without VEM			With VEM		
Mode No.	Frequency (Hz)	Damping ratio (ζ)	Dyn. stiffness (N/mm)	Frequency (Hz)	Damping ratio (ζ)	Dyn. stiffness (N/mm)
1	349	8,3 %	23748	344	8,5 %	30117
2	757	4,9 %	18845	710	9,6 %	19240
3	876	2,8 %	6569	838	5,6 %	15462
4	1064	3,6 %	44726	1330	5,5 %	39287
5	1565	1,9 %	20759	1705	5,4 %	103525
6	1734	1,8 %	53101	1857	2,0 %	26902
7	1935	1,1 %	32857	2036	0,9 %	60864
8	2384	0,4 %	182431	2513	0,4%	256835
9	3032	0,5 %	213243	2872	1,3 %	328010

same excitation force. The following tables summarize the dynamic stiffness for the first 9 modes in all four configurations in the X measurement direction, along with the damping ratio as percentage of critical damping. The damping reduction effect of increased pressure on a metal-to-metal interface mentioned earlier can be also verified by comparing the damping data for the VEM-free configuration in Tables 2 and 3.

The abovementioned values are illustrated in Fig. 4, where it can be observed that for most of the modes, the application of the VEM layers causes an increase in the dynamic stiffness of the system. Especially in the case of mode 9, which is a torsional mode, the increase in dynamic stiffness reaches 27,8% in the low pre-stress configuration and 53,8% in the high pre-stress configuration.

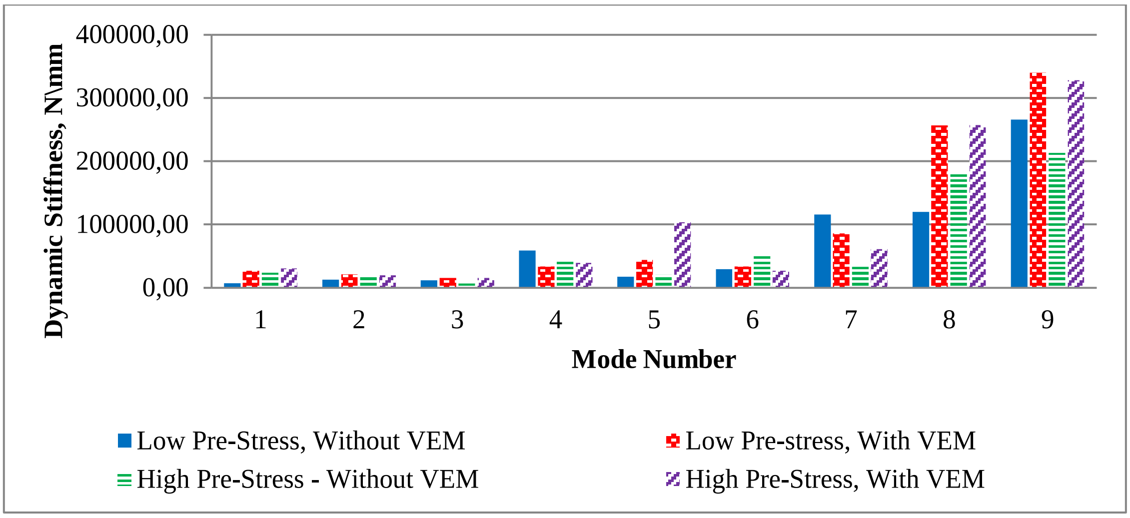

Fig. 4. Comparison of dynamic stiffness for the first 9 modes in all 4 configurations, X direction

From the values presented in the Tables 4 and 5 and figure above, it can be observed that despite the drop in static stiffness caused by the introduction of the VEM layers, there is considerable improvement in most cases in damping. In most of the modes, together with the application of VEM layers comes an increase in dynamic stiffness. The same analysis is performed below for the system's natural characteristics in the Y direction.

Table 4. Dynamic stiffness and damping ratio, Y direction, Low pre-stress configuration

-	Without VEM			With VEM		
Mode No.	Frequency (Hz)	Damping ratio (ζ)	Dynamic stiffness (N/mm)	Frequency (Hz)	Damping ratio (ζ)	Dynamic stiffness (N/mm)
1	778	3,7%	9051	589	3,0%	15923
2	888	2,8%	33068	695	4,1%	22009
3	965	2,7%	53216	808	7,1%	35772
4	1031	0,3%	34735	887	3,9%	37469
5	1487	3,0%	43394	1290	7,6%	90018
6	1527	0,9%	42887	1385	2,4%	87517
7	1928	2,8%	34543	1938	1,4%	23352
8	1999	1,8%	29492	1988	2,1%	31086
9	2216	0,4%	57277	2072	1,1%	43498
10	2532	0,7%	173300	2500	0,2%	165516
11	2948	1,5%	253426	2870	1,5%	311652

Table 5. Dynamic stiffness and damping ratio, Y direction, High pre-stress configuration

-	Without VEM			With VEM		
Mode No.	Frequency (Hz)	Damping ratio (ζ)	Dynamic stiffness (N/mm)	Frequency (Hz)	Damping ratio (ζ)	Dynamic stiffness (N/mm)
1	817	5,2%	15606	554	4,5%	10579
2	898	2,3%	21247	642	4,8%	31302
3	970	2,3%	23892	768	4,0%	51797
4	1059	0,9%	35579	959	2,8%	56337
5	1503	2,0%	95663	1261	6,6%	90457
6	1660	0,9%	32564	1374	2,0%	74321
7	1931	2,1%	59433	1933	1,6%	16283
8	2062	1,8%	38810	2034	0,8%	33226
9	2386	2,4%	111679	2218	1,6%	76419
10	2608	0,4%	224679	2498	0,2%	185694
11	3033	0,6%	202276	2837	1,3%	394441

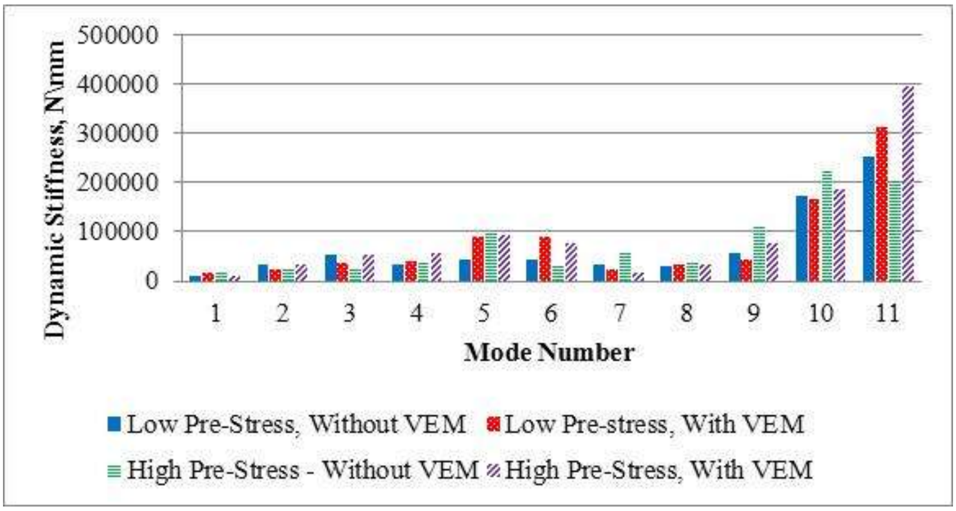

Fig. 5. Comparison of dynamic stiffness for the first 9 modes in all 4 configurations, Y direction

4. MACHINING TESTS OF THE SYSTEM UNDER STUDY

The machining tests performed, aimed at revealing the effects of damping and stiffness in actual cutting conditions. This end-milling process was carried out in a 3 axis vertical CNC-milling machine executing a rectangular cutting path, covering both directions of the horizontal plane. The tests were conducted in two sets for each VEM configuration; the first set was carried out in high cutting speed conditions while the second set was carried out in low cutting speed conditions. Radial and axial cutting depths were kept constant in all configurations. The following Table 6 presents the specifics of the cut:

Table 6. Machining parameters

Tool	Cutting parameters
End mill with inserts	Cutting speed: 59,69m/min, 170,93m/min
Diameter: 20mm	Rotational speed: 950rpm, 2800rpm
No. of inserts: 3	Feed: 200m/min
Insert cutting radius: 2mm	Radial depth of cut: 2mm
Overhang: 60mm	Axial depth of cut: 8mm
Effective no. of teeth: 1	Down milling

Data were acquired by the same system used to carry out the experimental modal analysis tests, while a 3-axial accelerometer is cemented on the workpiece in order to record the time signal from the process. The machining tests were carried out again for two pre-stress configurations (low and high) and two VEM configurations (with and without the VEM layers).

4.1. EXAMINATION OF THE SYSTEM'S BEHAVIOUR IN HIGH CUTTING SPEED

In high cutting speed conditions, the tooth engagement frequency is 140Hz. The tests conducted in this case aimed at revealing the effect of introducing higher damping through the VEM layers on the response of the system during machining together with the effect of the different pre-stress configurations.

Fig. 6 presents the acceleration signals from all three measurement axes, acquired during the cutting process along the X axis and for the low pre-stress configuration. The red curve represents the response of the system with VEM layers, while the blue ones represent the response of the system without the VEM layers.

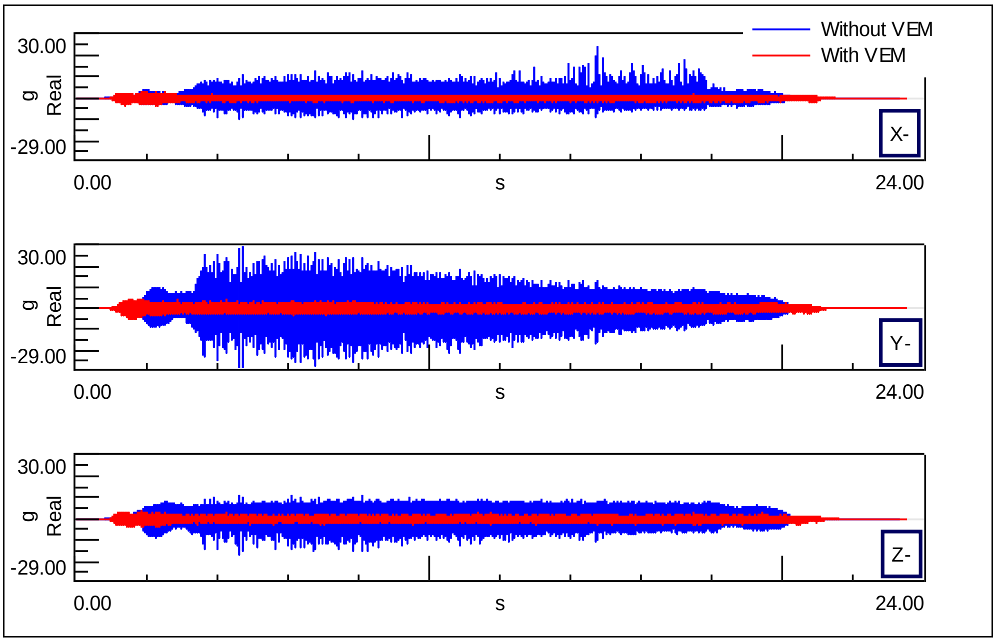

Fig. 6. Time response of acceleration, X feed direction, high cutting speed, low pre-stress

An observation of the graphs above reveals that the increase in damping through the application of the VEM layers has a significant reducing effect on the acceleration amplitudes, i.e. the vibration levels in the system. Another qualitative observation from the graphs is that the system in the VEM configuration is managing to reduce the effect of the entry impact between the tool and the workpiece at the beginning of the machining process. In the damped configuration the transient state of the system is significantly less intense.

The values presented in Table 7 show clearly the effect of changing the control parameters on the system's response to machining excitation under high cutting speed conditions. In both pre-stress configurations, the reduction of acceleration amplitudes is significant between the two damping configurations, although more profound in the case of the low pre-stress configuration. This indicates that a significant increase in damping and dynamic stiffness in the system can compensate possible loss in static stiffness regarding the system's response to excitation.

Table 7. Comparison of vibration amplitudes' levels in high cutting speed conditions, high pre-stress

		Low pre - stress			High pre - stress		
Feed direction	Measurement direction	VEM-free (g)	With VEM (g)	Amplitude reduction	VEM-free (g)	With VEM (g)	Amplitude reduction
X	X	10,4	1,9	82%	2,2	1,9	8%
-	Y	14,0	3,7	74%	6,9	2,6	62%
-	Z	8,6	2,7	68%	6,1	2,1	65%
Y	X	5,5	3,1	44%	4,3	2,8	35%
-	Y	15,4	3,4	78%	5,5	2,8	49%
-	Z	13,9	4,7	66%	11,1	2,2	80%

A comparison of the abovementioned case with regards to adaptive stiffness shows that an increase of pre-stress tends to reduce the amplitudes of the system's response regardless of whether there is metal to metal or metal to VEM contact at the interface. Nevertheless the effect of pre-stress is more profound in the case of VEM-free configuration. This observation aligns with the findings from the modal tests, where the increase of pre-stress had a stronger effect on stiffness in the VEM – free configuration.

Fig. 7 depicts the response of the system for one rotation of the tool, i.e. 3 insert – workpiece impacts. The way the viscoelastic material affects the system's response is clearer in this figure, where it can be observed that the peaks due to insert impact are damped significantly, which can have considerable decrease in tool wear due to the reduction of the relative motion between the tool and the workpiece.

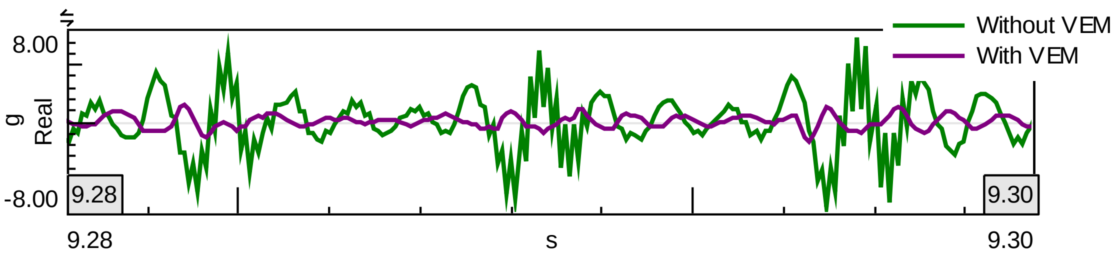

Fig. 7. Time domain response between three insert impacts, X feed direction, Y measurement direction, high pre-stress, high cutting speed

An examination of the system's response signal in the frequency domain reveals that the configuration with VEM exhibits a significant reduction of amplitudes across all the frequency range that was examined. However this behaviour is more profound in the higher frequency range where vibrations in the area above 3500Hz are almost disappearing. The amplitudes of the harmonics of the tooth engagement frequency are reduced, while excitation response in frequency bands between these harmonics is also reduced. Fig. 8 exhibits the described behaviour of the system in all four configurations.

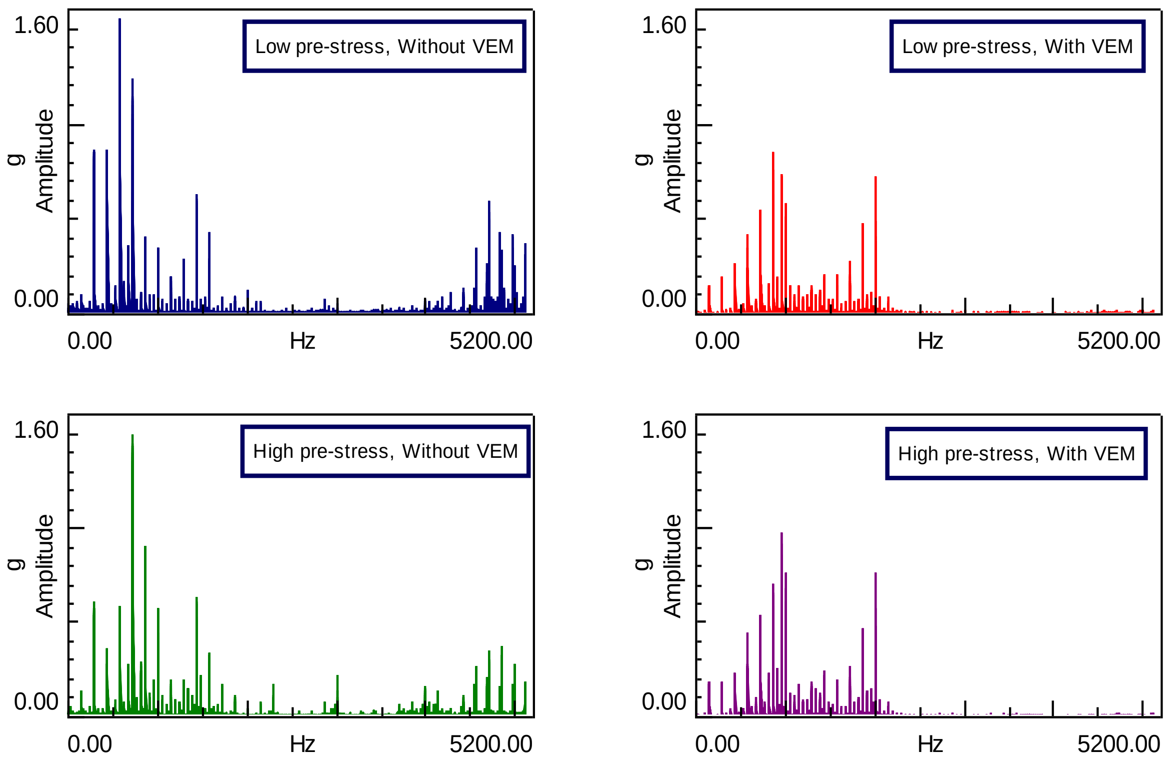

Fig. 8. Frequency domain response, Y feed direction, acceleration on the X-direction

4.2. EXAMINATION OF THE SYSTEM IN LOW CUTTING SPEED

In the case of low cutting speed, vibration amplitudes show higher variation as shown in Fig. 9, while energy from the process is not distributed in distinct harmonic frequencies, but is concentrated in one or a few frequency bands as shown in Fig. 13. Fig. 9 below presents the acceleration signals from all three measurement axes, acquired during the cutting process along the X, for the high pre-stress configuration. Similarly to the case of the high cutting speed, the application of the VEM tends to reduce vibration amplitudes from the process. However, in the low pre-stress case, the effect of increased damping was found to have lower significance. This could be explained by the fact that in the low pre-stress configuration, static stiffness is too low for the damping mechanism to dissipate vibration energy efficiently.

Regarding the effect of adaptive stiffness in the system’s response, in the configuration without VEM layers, as pre-stress increases, the vibration amplitudes are increasing (Fig. 10). This is in contrast to the behaviour observed in high cutting speed conditions. In the configuration with VEM layers, there is a decrease in the amplitude levels as the pre-stress increases (Fig. 11).

This observation indicates that the decrease in damping caused by the increased pressure on the interface without VEM is of high importance when the machining system shows this kind of response.

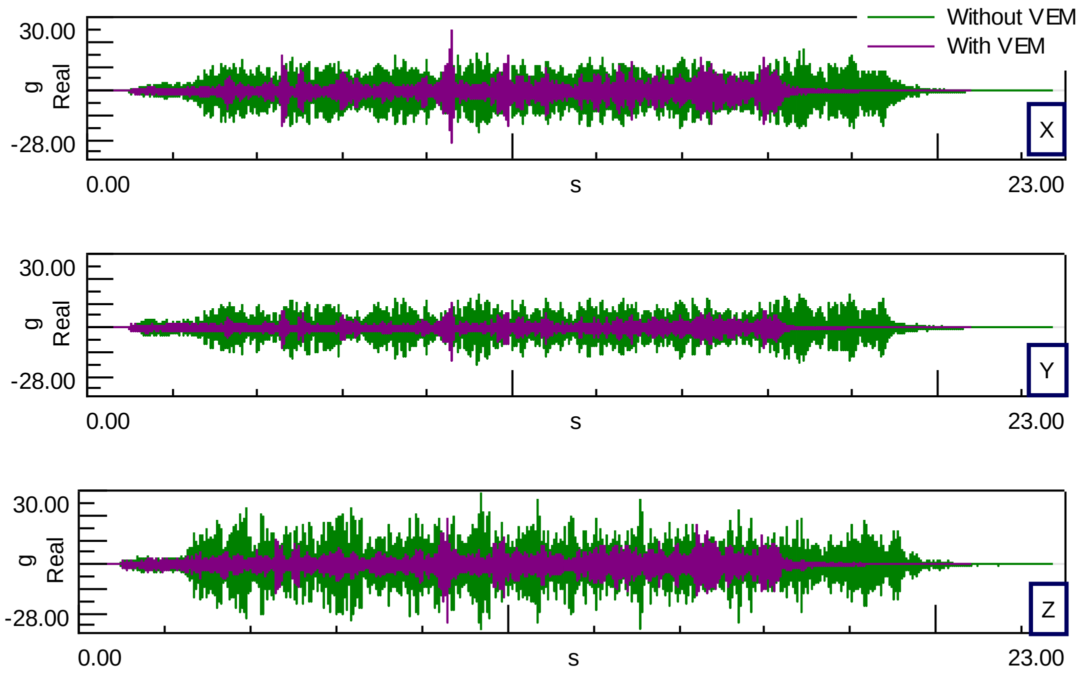

Fig. 9. Time domain response of acceleration, X feed direction, low cutting speed, high pre-stress

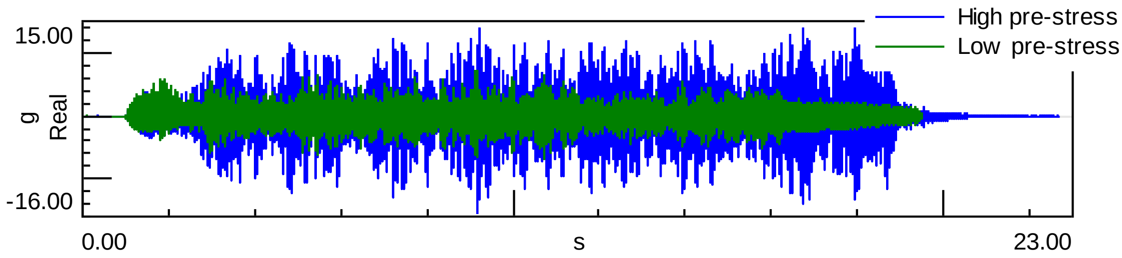

Fig. 10. Time domain response, X feed direction, Y measurement direction, low cutting speed without VEM

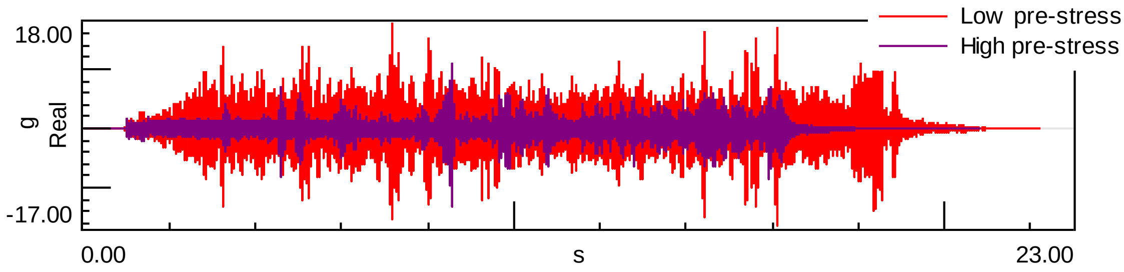

Fig. 11. Time domain response, X feed direction, Y measurement direction, low cutting speed, with VEM

A closer inspection of the measured amplitudes is provided in Fig. 12, which depicts the time interval between two insert impacts with the workpiece for the with and without the VEM layers. Apart from the reduced amplitude of vibrations which was mentioned earlier, the decay time of the excitation response from an insert impact is also reduced.

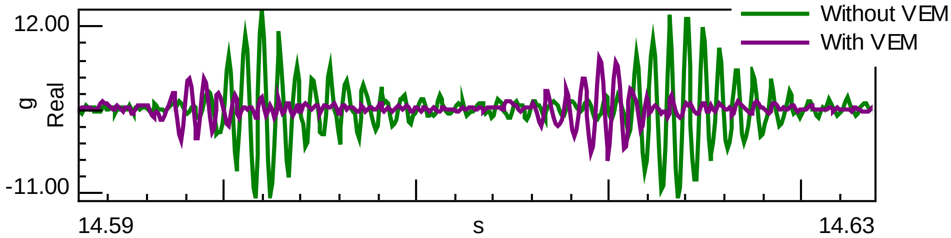

Fig. 12. Time domain response between two insert impacts, X fed direction, Y measurement direction, high pre-stress

An examination of the system’s response in low cutting speed reveals, as mentioned earlier, that energy from the process is gathering around few frequency bands, as shown in Fig. 13. A comparison of data in Table 8 with those in Tables 2 and 3 reveals that the excited bands are close to modes 2, 4, 7 and 9. In the VEM-free configuration, the increase of stiffness causes energy to gather in slightly higher frequency bands which can be attributed to the increase in static stiffness of the system. As pre-stress increases, the response in the first frequency band around 660Hz is reduced which can be attributed to the small increase in damping and dynamic stiffness of mode 2 in the high pre-stress configuration. On the contrary, response around the third frequency band around 2180Hz increases, which can be attributed to the loss of damping and dynamic stiffness of mode 7 in the higher pre-stress configuration.

Table 8. Correlation between excitation response and natural characteristics in the VEM free configuration

VEM-free configuration			
Low pre-stress		High pre-stress	
Main excitation frequency (Hz)	Correlated mode	Main excitation frequency (Hz)	Correlated mode
656	2	680	2
1160	4	1181	4
1997	7	2184	7
2830	9	3016	9

In the configuration with VEM, energy is concentrated around two frequency bands in the low pre-stress configuration and three bands in the high pre-stress configuration. The shift in excited frequencies for different pre-stress levels seems to be insignificant compared to the VEM-free configurations (Table 9). This can be attributed to the reduced effect of pre-stress on static stiffness in the configuration with VEM. The main frequency band excited is around 1080-1090Hz in both pre-stress configurations. As pre-stress increases the response in the second band of around 2050Hz is reduced drastically. On the other hand a band around 2976Hz is now excited, even at a low amplitude level (only explanation is the increase in static stiffness). A comparison with the tables containing modal frequencies shows that these bands are close to modes with lower damping (modes 4, 7, 9 on the X direction).

Table 9. Correlation between excitation response and natural characteristics in the VEM free configuration

VEM configuration			
Low pre-stress		High pre-stress	
Main excitation frequency (Hz)	Correlated mode	Main excitation frequency (Hz)	Correlated mode
1081	4	1091	4
2055	7	2120	7
		2976	9

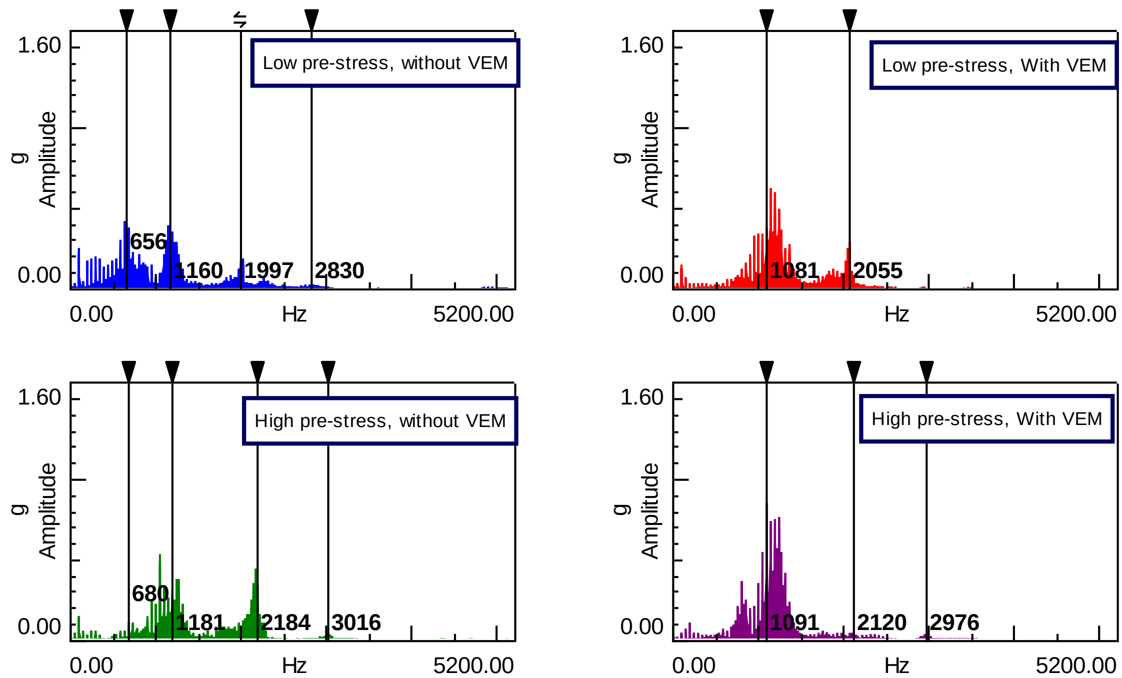

Fig. 13. Frequency domain response, low cutting speed, Y feed direction, X measurement direction

5. CONCLUSIONS

The case of a machining system consisting of a machine tool, a workpiece and a work holding device with adaptive stiffness was examined, in regards to the interactions between control parameters, its natural characteristics and process parameters and how these interactions are reflected on the system's response to machining excitation. The system was examined between two pre-stress configurations exerted on an interface of the work holding device, and for two damping configurations, with and without viscoelastic layers on the aforementioned interface. The machining tests were conducted for all four configurations in high and low cutting speed conditions and an effort was made to establish the effect of the control parameters on the system's natural characteristics and how these are affecting the response of the system to machining excitation. From the analysis of the experimental data the following conclusions can be drawn:

- The increase of pre-stress between two components of the work holding device causes, as expected, an increase in static stiffness of the system under study and a reduction in damping. This is more profound in the case of the VEM - free configuration. The existence of VEM materials reduces the effectiveness of increased pre-stress on static stiffness.
- The application of VEM layers in the work holding device causes a decrease in static stiffness of the system in both pre-stress configurations and an increase in damping and dynamic stiffness in most of the modal frequencies of the system, especially on the X direction. The static stiffness reduction observed when applying the VEM layers highlights the importance of careful interface design for maintaining rigidity in the system, when highly flexible materials are applied on the interface.
- The increase in damping reduces the amplitude of measured vibration under both low and high cutting speed conditions.
- In high cutting speed conditions the increase of pre-stress and therefore static stiffness causes a reduction in the amplitudes of measured vibration in both VEM configurations.
- In the case of low cutting speed conditions, the increase of pre-stress and therefore the reduction of damping has a detrimental effect on the system's response in the VEM – free configuration, while in the case of the configuration with VEM it causes a reduction of measured amplitudes.
- In respect to the frequency domain of the response, in high cutting speed conditions, energy is distributed in distinct harmonics, while increased pre-stress seems to have little effect on the system's response.
- In low cutting speed, where vibration amplitudes showed high variation, energy is concentrated in few frequency bands, which are close to certain natural frequencies of the system.

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REFERENCES

[1] STEPHENSON D.A., AGAPIOU J.S., 2006, *Metal Cutting, Theory and Practice*, 2nd Edition, Taylor & Francis
[2] TOBIAS S.A., 1965. *Machine Tool Vibration*, J. Wiley.
[3] RIVIN E. I., 1999, Stiffness and Damping in Mechanical Design, Marcel Dekker, Inc.
[4] ALTINTAS Y., BUDAK, E., 1995, *Analytical prediction of stability lobes in milling*, CIRP Annals-Manufacturing Technology, 44/1, 357-362.
[5] FULLER C.R., ELLIOTT S.J., NELSON A., 1997, *Active control of vibration*, Academic Press.

[6] RASHID A., 2005, *On passive and active control of machining system dynamics, analysis and implementation*, Ph.D. Thesis.
[7] LIU K., ROUCH K., 1991, *Optimal passive vibration control of cutting process stability in milling*, Journal of Materials Processing Technology, 28/1-2, 285-294.
[8] MEHTA N., PANDEY P., CHAKRAVARTI G., 1983, *An investigation of tool wear and the vibration spectrum in milling*, Wear, 91/2, 219-234.
[9] GHANI A., CHOUDHURY I., HUSNI., 2002, *Study of tool life, surface roughness and vibration in machining nodular cast iron with ceramic tool*, Journal of Materials Processing Technology, 127/1, 17-22.
[10] RAO M.D., 2003, *Recent applications of viscoelastic damping for noise control in automobiles and commercial airplanes*," Journal of Sound and Vibration, 262/3, 457-474.
[11] SHI X., POLYCARPOU A.A., 2005, Measurement and modeling of normal contact stiffness and contact damping at the mesoscale, Journal of Vibration and Acoustics, 127/1, 52-60.