PERMAS USERS' CONFERENCE

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MODELLING AND SIMULATION OF THE SELF-EXCITED CHATTER VIBRATION

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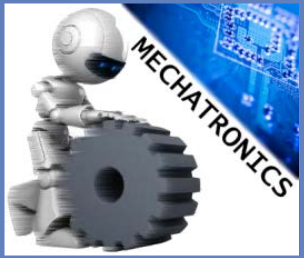

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Gdansk University of Technology

- about 25000 students
- 9 faculties
- 7 kinds of doctorate courses
- 29 fields of study
- 40 postgraduate courses
- 1200 academic teachers

Faculty of Mechanical Engineering

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- 250 graduates annually
- 6 fields of study
- 3 postgraduate courses
- doctorate course
- 123 academic teachers

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Dynamic systems surveillance - a set of intentional activities, aimed at securing the desired performance of a dynamic process.

The **systems surveillance** depends upon:

- **monitoring** of physical quantities, which affect the process quality (e.g. vibration level, amplitude of displacements)

- **generation** of instantaneous values of control command, in accordance with a proper rule being applied.

Vibration reduction in milling

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We know many different methods for reduction and surveillance of the chatter vibration, i.e.:

- Using the cutting edge chamfers
- Using mechanical dampers
- Using smart materials
- Robust optimal control
- Active structural control
- Active holder
- Active damping
- Cutting with variable spindle speed
- Matching the spindle speed to the optimal phase shift between subsequent passes of the tool cutting edges
- Variable spindle speed
- Raising spindle speed
- Matching the spindle speed to natural frequency of vibrating system

Optimal spindle speed

Optimal spindle speed

– The speed, at which chatter vibration amplitude approaches minimum

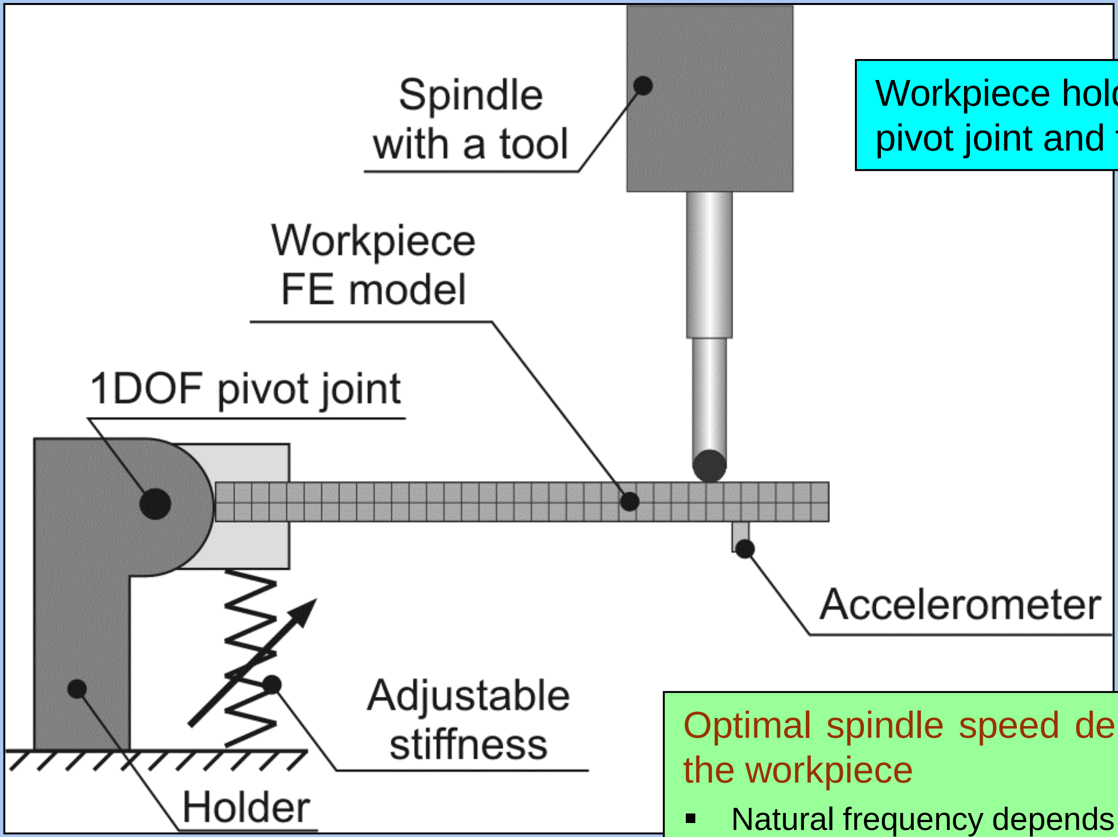
Generalised Liao-Young condition

In case, when only one dominant resonance is observed in the workpiece vibration spectrum

$$\frac{zn_\alpha}{60} = \frac{f_\alpha}{0{,}25 + k}, \quad k = 0, 1, 2, \ldots$$

$f\alpha$ – determined natural frequency of the workpiece [Hz],
$n\alpha$ – sought optimal spindle speed [rev/min],
z – number of mill edges

New variable stiffness holder



Workpiece holder with adjustable stiffness and 1 DOF pivot joint and the FEM model of the workpiece

Optimal spindle speed depends on dominant natural frequency of the workpiece

- Natural frequency depends on workpiece dynamic properties.
- The workpiece is mounted in a holder with adjustable stiffness and whose behaviour is based on 1 DOF pivot joint.
- Thanks to the adjustable stiffness, it is possible to modify dynamic properties of the whole system (consisting of the holder and the workpiece) and to modify its natural frequency.

Cutting process model

Proportional model

Cutting force components depend proportionally on cutting layer thickness, and on variable in time depth of cutting

$$F_{yl1}(t)=\begin{cases}\mu_l k_{dl} a_l(t) h_l(t), & a_l(t)>0 \ \wedge \ h_l(t)>0,\\ 0 \qquad , & a_l(t)\le 0 \ \vee \ h_l(t)\le 0,\end{cases}$$

$$F_{yl2}(t)=\begin{cases}k_{dl} a_l(t) h_l(t), & a_l(t)>0 \ \wedge \ h_l(t)>0,\\ 0 \qquad , & a_l(t)\le 0 \ \vee \ h_l(t)\le 0,\end{cases}$$

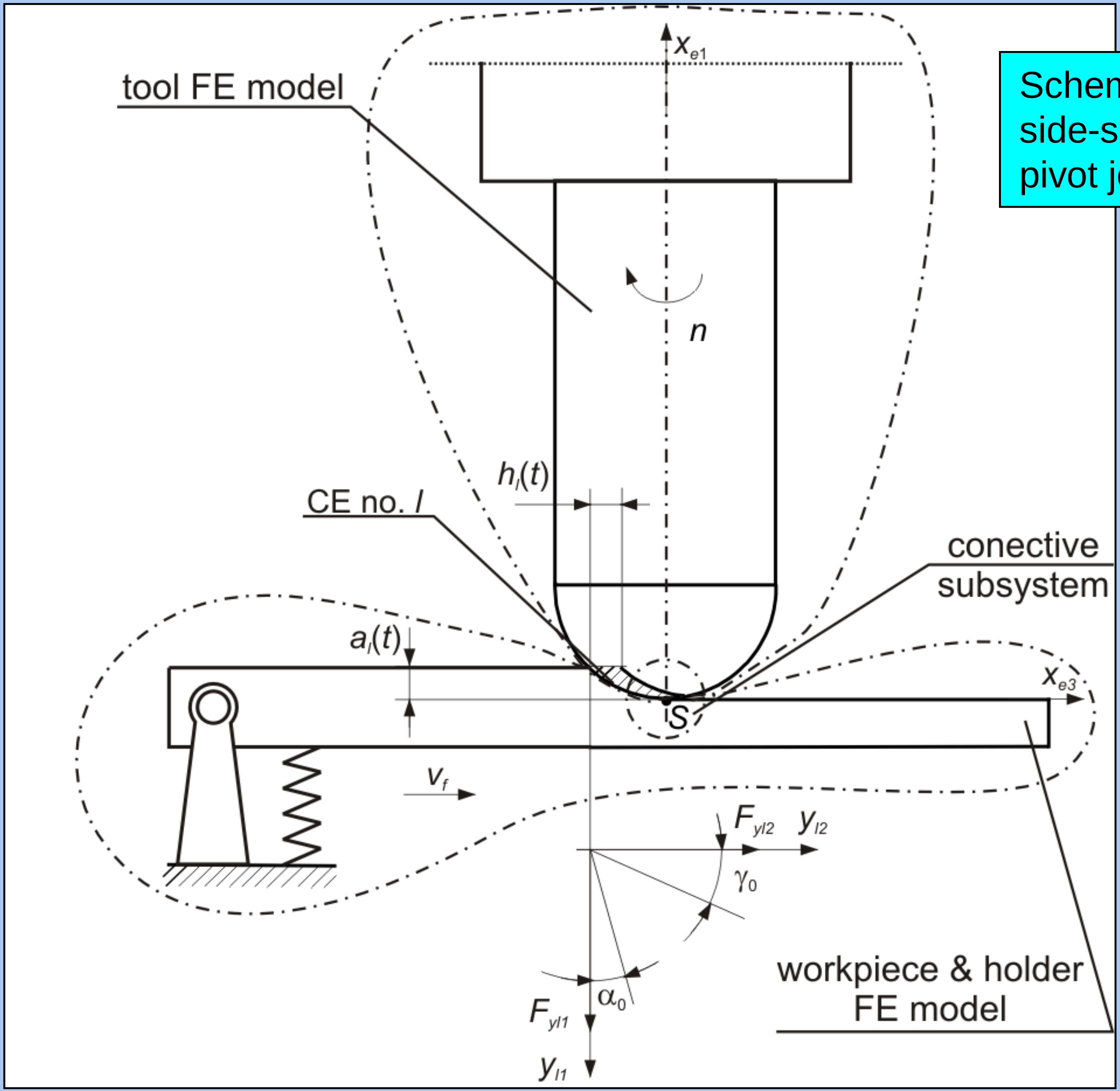
$$F_{yl3}(t)=0$$

where:

$$a_l(t)=a_{pl}(t)-\Delta a_{pl}(t)$$

$$h_l(t)=h_{Dl}(t)-\Delta h_l(t)+h_l(t-\tau_l)$$

Holder, workpiece and tool system model



Scheme of a slender ball-end milling of one-side-supported flexible workpiece in a 1 DOF pivot joint.

Hybrid approach

» **modal subsystem:**
stationary model of one-side-supported flexible plate, which displaces itself with feed speed *vf*.

» **structural subsystem**
non-stationary discrete model of ball-end mill and cutting process.

» **connective subsystem**
conventional contact point S between the tool and the workpiece.

Simulations

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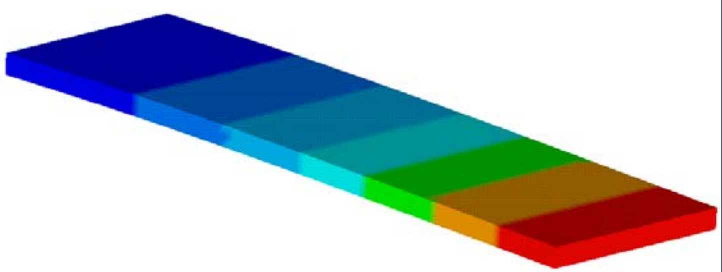
Natural frequencies of two first modes of variable stiffness holder with workpiece

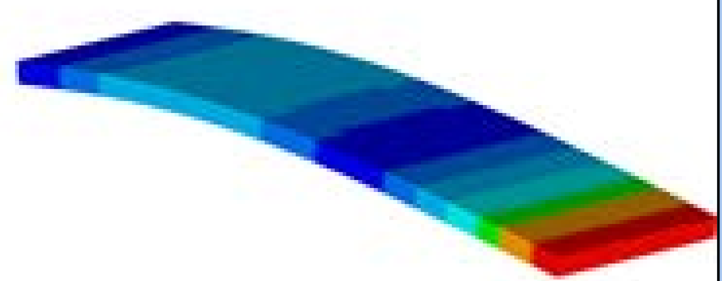
Both natural frequencies change due to adjustment of the spring stiffness. It was also noticed that both normal modes of the holder with the workpiece are well coupled with the workpiece

Spring stiffness [N/mm]	1st natural frequency [Hz]	2nd natural frequency [Hz]
14800	138.62	468.67
11000	131.36	427.48
8500	124.08	398.47
6800	117.16	377.87
5600	110.78	362.93
4700	104.83	351.54
4000	99.27	342.60
3470	94.36	335.80
3050	89.94	330.39
2670	85.43	325.50

First normal mode (110.78 Hz) of the stiffness holder with the workpiece at spring stiffness 5600 N/mm



Second normal mode (362.93 Hz) of the stiffness holder with the workpiece at spring stiffness 5600 N/mm



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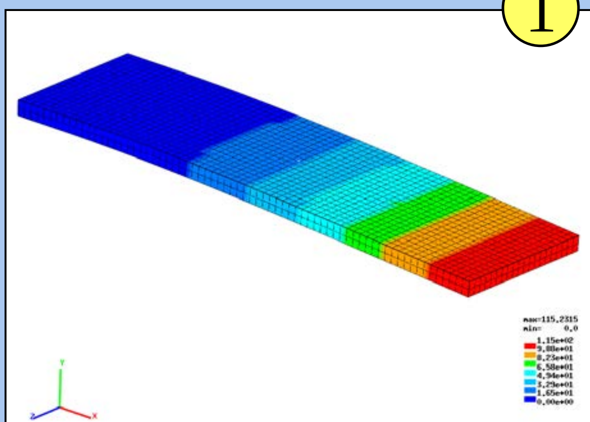
Identification of the modal parameters

Model without accelerometer	152,51 Hz	881,43 Hz	947,06 Hz
Model with accelerometer	143,04 Hz	879,81 Hz	891,59 Hz

1



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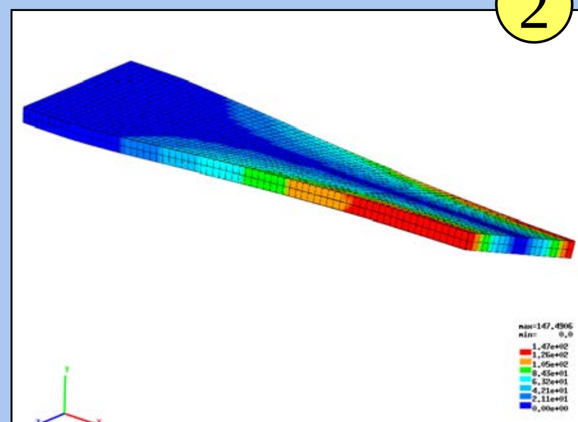

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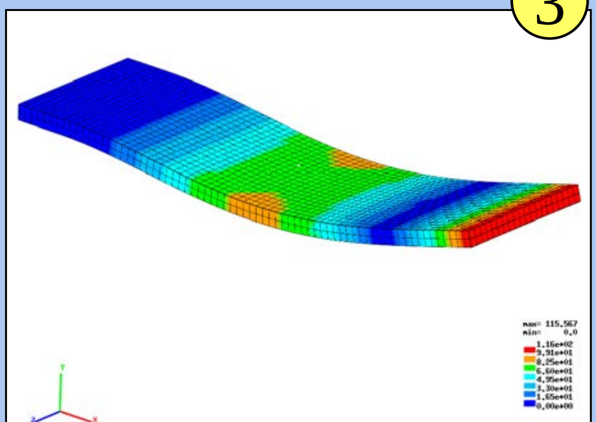

Pre-processing – **T-Systems Medina**, Solver – **PERMAS**
Post-processing – **FEGraph**

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Standard deviation of displacements [mm]. Expected optimal pairs marked with gray background.

Spindle speed [rev/min]	Holder spring stiffness [N/mm]						
	14800	11000	8500	6800	5600	4700	4000
17651	0.002366						
16745		0.007657					
16651	**0.002539**	0.005380					
15869			0.002711				
15745	0.003676	**0.002613**	0.002671	0.002523	0.002193		
15651	0.003866						
15284					0.002547		
15047				0.002860			
14869		0.004322	**0.002926**	0.002787	0.002927		
14745		0.004957					
14581						0.002810	
14284					0.003170		
14047			0.006864	**0.003431**	0.003163		
13869			0.008736				
13784					0.003831		
13581						**0.003441**	
13284				0.008378	**0.004034**	0.004537	**0.003627**
13047				0.010622			
12581					0.015531	**0.020466**	0.031396
12284					0.024176		
11932						0.059660	**0.059596**
11581						0.078220	

Simulations

Amplitude of the 1st natural frequency [mm]. Expected optimal pairs marked with gray background. Obtained optimal pairs in bold.

Spindle speed [rev/min]	Holder spring stiffness [N/mm]						
	14800	11000	8500	6800	5600	4700	4000
17651	0.001584						
16745		0.007286					
16651	**0.000310**	0.004502					
15869			0.001615				
15745	0.001045	**0.000317**	0.001557	0.001632	0.000666		
15651	0.001282						
15284					0.000942		
15047				0.001510			
14869		0.002834	**0.000472**	0.000848	0.001501		
14745		0.003316					
14581						0.001212	
14284					0.001103		
14047			0.004760	**0.000747**	0.005021		
13869			0.006904				
13784					0.001447		
13581						**0.000357**	
13284				0.006728	**0.000521**	0.002755	**0.002057**
13047				0.008114			
12581					0.005560	**0.021472**	0.033184
12284					0.029790		
11932						0.074891	**0.073382**
11581						0.082545	

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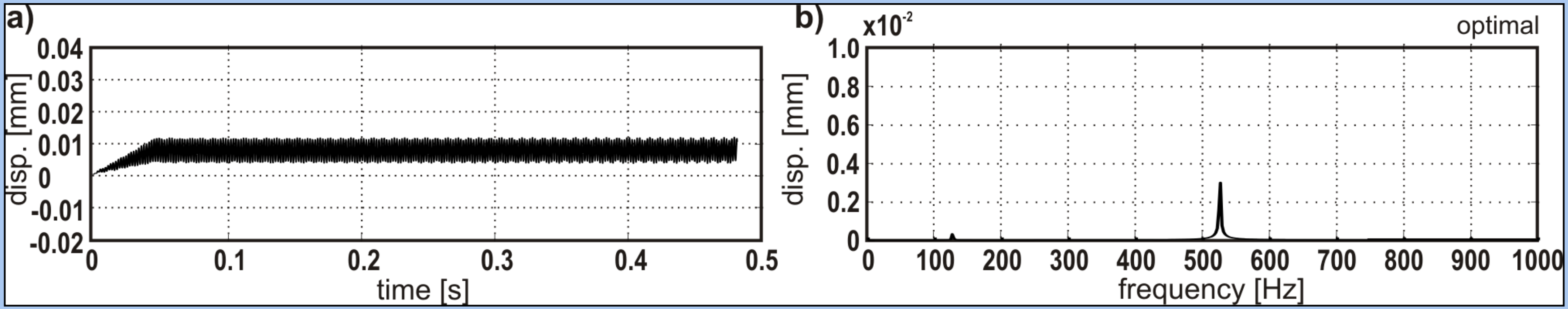
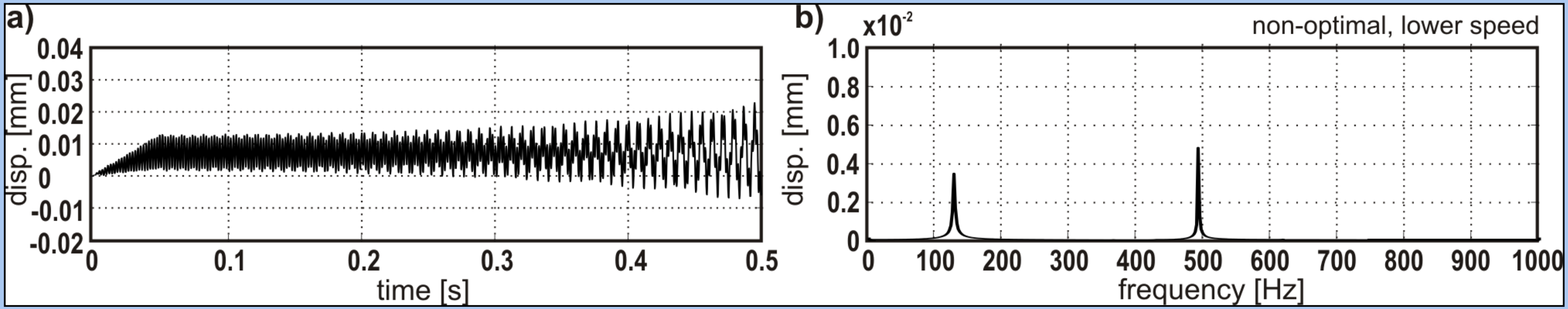
Simulations



Displacement (a) and its spectrum (b) for optimal pair of spindle speed **n=15745 rev/min** and holder stiffness **11000 N/mm**.



Displacement (a) and its spectrum (b) for non-optimal pair of spindle speed **n=14745 rev/min** and holder stiffness **11000 N/mm**

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Simulations

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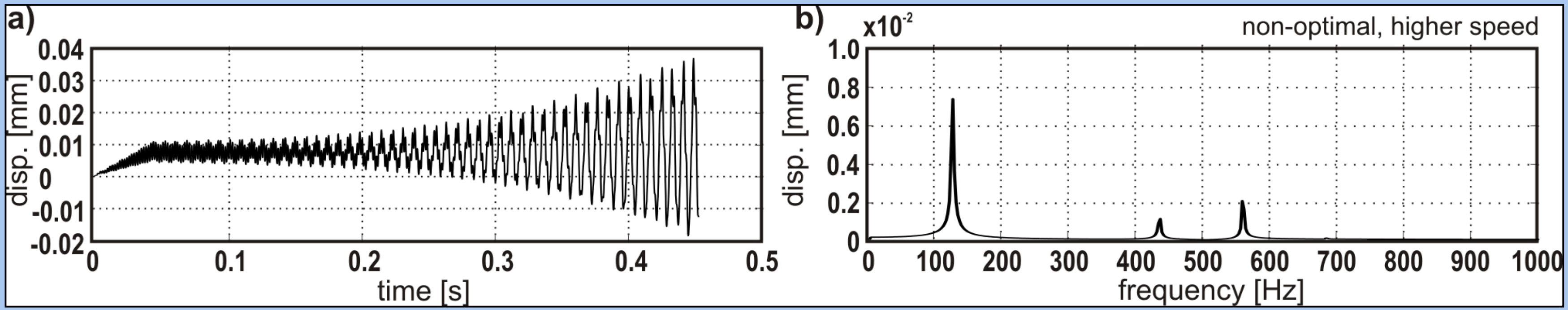
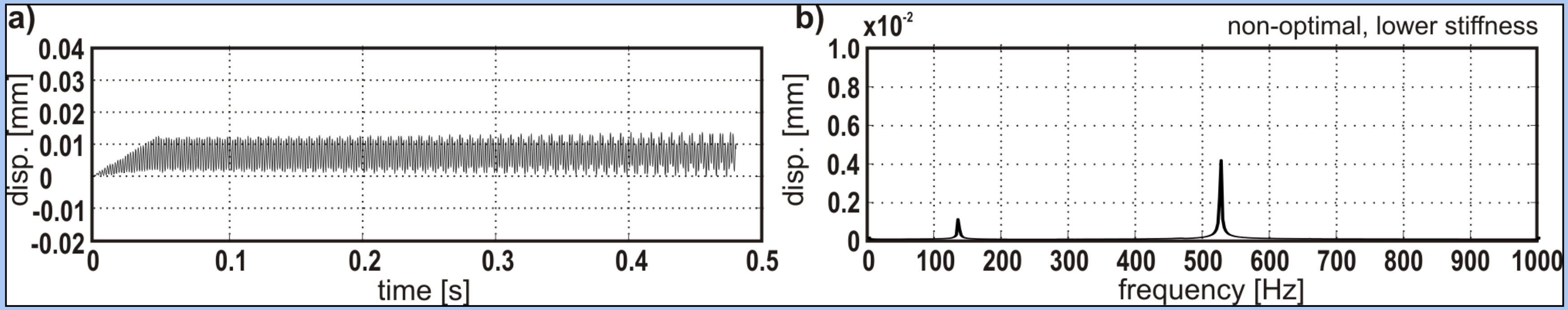
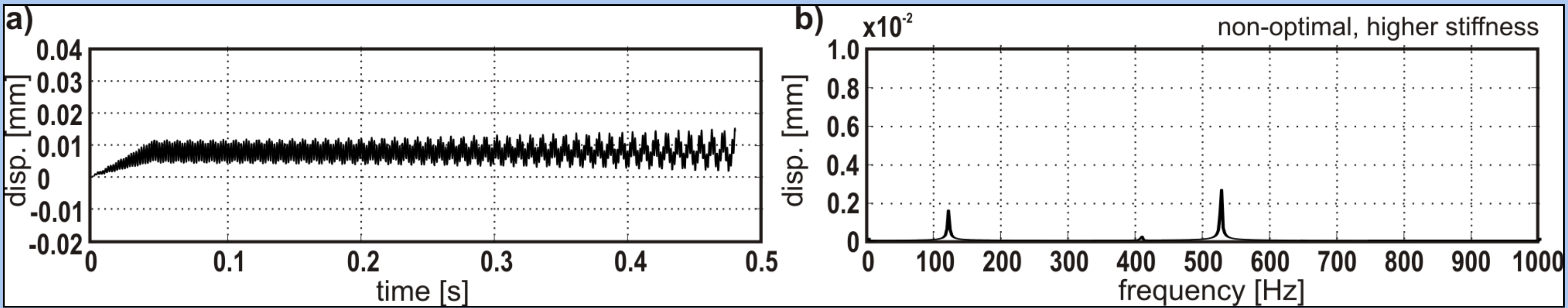


Displacement (a) and its spectrum (b) for non-optimal pair of spindle speed **n=16745 rev/min** and holder stiffness **11000 N/mm**



Displacement (a) and its spectrum (b) for non-optimal pair of spindle speed **n=15745 rev/min** and holder stiffness **8500 N/mm**.

Simulations



Displacement (a) and its spectrum (b) for non-optimal pair of spindle speed **n=15745 rev/min** and holder stiffness **14800 N/mm**

Conclusion

- Modifying the holder-workpiece system dynamic properties is possible with the use of the proposed new workpiece holder
  - however – the range of modifications is limited, and
  - confirmed by preliminary modal experiments on holder prototype
- Simulations for different pairs of holder stiffness and spindle speed show that only in case of a proper, optimal combination of these two parameters, vibrations are the lowest
- Proposed variable stiffness holder has a potential to overcome the problem of limited set of optimal spindle speeds calculated from Liao-Young condition
  - Arbitrary given spindle speed may be optimal after holder stiffness adjustment

Publications

1. Kaliński K. J., Galewski M. A., Mazur M. R.: High Speed Milling vibration surveillance with optimal spindle speed based on optimal speeds map. Key Engineering Materials 2014, 597, 125-130.
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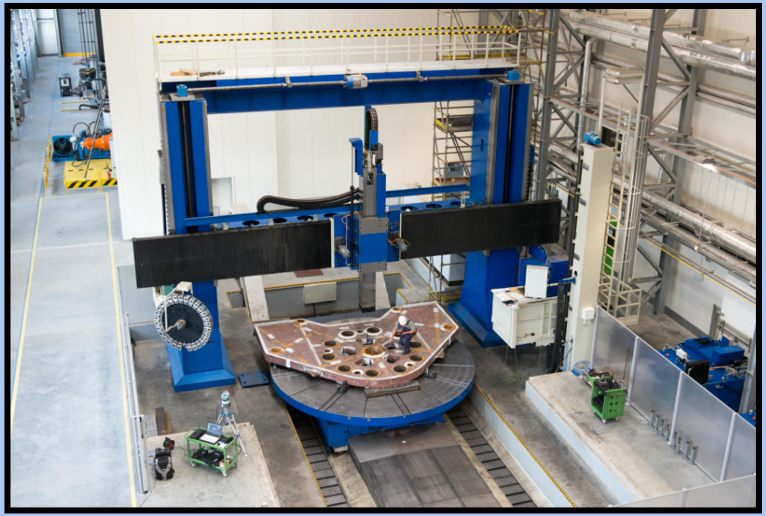
3. Kaliński K., Chodnicki M., Galewski M., Mazur M.: Vibration surveillance for efficient milling of flexible details fixed in adjustable stiffness holder. Vibroengineering PROCEDIA 2014, 3, 215-218.
4. Kaliński K. J., Galewski M. A.: Vibration surveillance supported by Hardware-In-the-Loop Simulation in milling of flexible workpieces. Mechatronics 2014, 24, 1071-1082.
5. Kaliński K. J., Galewski M. A.: A modified method of vibration surveillance with a use of the optimal control at energy performance index. Mechanical Systems and Signal Processing 2015, 58-59, 41-52.
6. Kaliński K. J., Galewski M. A.: Optimal spindle speed determination for vibration reduction during ball-end milling of flexible details. International Journal of Machine Tools and Manufacture 2015, 92, 19-30.
7. Galewski M. A.: Spectrum-based modal parameters identification with Particle Swarm Optimization. Mechatronics 2015, 1-12.

Prospective application

Project TANGO1/266350/NCBR/2015

Application of chosen mechatronic solutions to surveillance of the cutting process of large size objects on multi-axes machining centres



Example: Carousel lathe machine FKD 80/60 Feichter. Energomontaż-Północ Ltd Gdynia

Signing cooperation agreement between GUT and HYDROTOR PLC., the industrial partner

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Thank you very much for attention!!!

Dziękuję za uwagę

Thank you for your attention

Vielen Dank für Ihre Aufmerksamkeit