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An integrated CNC system for chatter suppression in turning

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A B S T R A C T

Self-excited chatter vibrations are one of factors affecting the reduction of cutting efficiency, especially while machining highly compliant machine parts. Their occurrence can be limited by the proper technological parameters selection. These parameters can be determined by analysing the cutting process stability, which requires knowledge of the machine-tool-workpiece system dynamic properties. Normally, these properties are determined experimentally, which is troublesome in industrial practice. This article presents a method in which dynamic properties are calculated by single-board computer integrated with a Computer Numerical Control (CNC) system, with no need to carry out additional experimental tests. It is possible with the receptance coupling approach which allows for obtaining the workpiece geometry by analyzing the machining program and then determining the machine tool – workpiece system dynamic properties. These properties are the input to the presented algorithm that facilitates the selection of cutting parameters enabling stable turning of highly compliant machine parts. The presented system is dedicated to turning but can also be adapted to determine the stability of milling with flexible tools.

A R T I C L E   I N F O

Keywords:
Computer numerical control (CNC);
Machining chatter;
Vibrations;
Stability analysis;
Machine-tool spindle;
Cutting parameters;
Turning

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1. Introduction

Research works on the suppression of self-excited chatter vibrations that were initiated by Tlusty [1] and Tobias [2] who found that vibration during machining results from the loss of process stability. The chatter suppression is still the subject of scientific research conducted around the world, which still does not provide a universally effective solution of this problem. Performing the cutting with chatter vibration negatively affects the quality of the machined surface, shortens the tool life and can ultimately lead to machine tool failure [3]. Avoiding the chatter vibrations is a particularly challenging task while machining flexible parts (e.g. slender shafts turning), as presented by Powałka et al. in [4] or Kaliński et al. in [5]. A detailed review of the most important chatter suppression techniques and chatter vibration research was presented by M. Siddhpura et al. in [6] and J. Munoa et al. in [7].

Basically, two approaches concerning chatter suppression can be distinguished: introduction of process modification to maintain its stability or search for a range of stability within the existing process [8]. The first group consists of hardware solutions and may refer to solutions introduced at the stage of machine tool construction or implementation of improvements to the existing machine tools. An innovative approach to the construction of machine tools in terms of providing higher resistance to vibration during machining was presented by Dunaj et al. in [9–11]. They proposed the construction of the machine tool body as a welded steel-polymer concentrate frame, which significantly increases the vibration damping capacity. Another solution for increasing the vibration damping capacity is the introduction of additional damping elements to the structure such as epoxy coating of the linear guide system foundation for the milling machine proposed by Powałka et al. [12] or the introduction of additively manufactured vibration eliminators presented by Dunaj et al. in [13]. Process modification at a later stage that can be implemented on an existing machine tool is the use of active vibration eliminators, as proposed by Parus et al. in [14] or Brecher et al. in [15]. The second group of methods, consisting of searching for areas of machining stability, can be defined as a software solution. Ensuring cutting stability is done through a selection of machining parameters (spindle rotational speed and cutting depth) for which the chatter vibrations do not occur. The elementary method for selecting these parameters is stability lobes, presenting the cutting depths at which chatter occurs as a function of spindle rotational speed [16-18]. The stability lobes are determined based on the dynamic properties of using a machine tool-workpiece system. These properties, like frequency response function (FRFs) can be determined in numerous ways. The experimental methods assume carrying out impulse tests, where the accelerometers measure the system's response excited with a modal hammer [19]. However, this solution is dedicated mainly to research units with highly specialized measuring equipment and qualified staff to perform the experiment. An alternative to experimental measurements is the model-based approach, which consists in determining the machine tool-workpiece system FRFs using a finite element method [20-22]. Such methods, however, remain computationally complex, and achieving good results requires expensive software and highly experienced staff. A solution that incorporates the advantages of an experimental and model approach is the use of the receptance coupling [23]. The dynamic properties of the machine tool are determined experimentally and the compliant part of the system (a tool or a workpiece) is modeled analytically, as presented for milling by Park et al. in [24] or for turning by Jasiewicz et al. in [25].

The operation of CNC machine tools requires the operator experience in programming as well as knowledge of technological issues. Manufacturers of the most common CNC control systems provide solutions using a graphic interface, significantly simplifying programming in G-code (Shopturn/ShopMill by Siemens or Manual Guide by Fanuc). CNC control systems are also often modified by machine tool manufacturers by introducing their own human-machine interfaces (e.g., Celos by DMG Mori or Mazatrol by Mazak). This introduces the possibility of using different CNC systems in the same machine tool model while maintaining a consistent graphic design of the operator panels. Furthermore, touch screens, 3D graphics or gesture control are visually attractive and increase the comfort of using the machine. However, despite the improvement in terms of machine tool operation and programming, the issue of optimal technological parameters selection remains without additional support. In some cases, an arbitrary selection of the parameters proposed by the tool manufacturer will be sufficient. However, when machining compliant parts where there is a risk of vibration, additional support in this area can be particularly helpful. One of the solutions offered by machine tool manufacturers in the Machining Navi system by Okuma. Based on the acoustic analysis of the process, in case of vibrations during machining, it proposes to change the spindle speed. However, as in all commercial solutions, the operation of the system is a trade secret and the manufacturer does not provide technical details for the solution. Machining optimization systems that can be integrated into a machine tool have been the subject of research for many research teams. Passive systems for chatter suppression are based only on software solutions. Intelligent optimization of machining parameters for turning using the evolutionary algorithms was presented by Mia et al. in [26]. A solution in which computer numerical control parameters are optimized using fuzzy logic was proposed by Chiu et al. in [27]. Jasiewicz et al. [28] proposed a parameter selection assistant for turning integrated into the CNC system. Sun et al. developed in [29] a chatter detection algorithm based on variable-scale wavelet packet entropy. Active methods for chatter suppression are also very popular. Apart from software solutions, they use additional devices integrated with the CNC machine system. An active control approach using two piezoelectric actuators and an adaptive neural-network-based controller was proposed by Liu et al. in [30]. Another active control method consisting of an adaptive sliding-mode controller and a displacement field reconstruction method for chatter suppression was developed by Ma et.al. in [31]. Chen et. al. in [32] used an in-house designed magnetic actuator for an active damping method of boring bars. The popularity of integrating passive and active systems solutions into CNC systems will grow due to increasing computational power of CNC systems and introducing build-in sensors in the machine-tools. This creates the possibility to continuous monitoring and impact on the machining process. Another difficulty in developing a universal solution is the large variety of materials and geometry of workpieces. In [33] highlights some factors which affect the formation of a protective built-up layer (BUL) on the rake face of the cutting tool when cutting magnesium alloys. In other work [34] the authors focus on the problem of control of the accuracy of forming elastic-deformable shafts with low rigidity. The paper focuses on analyzing fundamental factors affecting the accuracy of machining of low-rigidity shafts like stiffness, the geometry of the cutting tool, lathe temperature, degree of cutting tool wear, cutting tool strength, lubrication-cooling fluid, and machining parameters are presented.

This article presents the concept of a low-cost system supporting the selection of turning parameters on a lathe with a FANUC CNC system. The first part concerns the issues of ensuring machining stability and the procedure for determining the FRFs of the machine tool-workpiece system using the receptance coupling approach. The second part presents the idea of a system supporting the selection of machining parameters, and subsequently, the implementation of the assistant for a CNC lathe equipped with a FANUC control system. The summary presents the results of an experimental study as well as conclusions.

2. Materials and methods

This subsection presents issues related to the problems of self-excited chatter vibrations occurring during machining, and a method for determining the stability of machining using stability lobes. Moreover, the receptance coupling procedure is described, which allows for determining the machine tool-workpiece system's frequency response function, obligatory for evaluating the stability lobes.

2.1 Background on turning stability

The reason for the occurrence of vibration during machining is the loss of cutting process stability. Most cutting operations, including turning, involve machining so that the tool tip moves over a previously machined surface. If one of the vibration modes of the machine tool system (usually the dominant one, the first mode) is excited by cutting forces, a wavy trace is formed on the machined surface. In the case of turning, the edge of the tool will meet this trace at the next rotation, which leads to a temporary change of the chip thickness and hence, a temporary increase of cutting and as a result, the formation of a new wave (trace). This phenomenon is known as regenerative chatter. Research concerning this phenomenon carried out over the years shows that ensuring the stability of machining depends on the appropriate selection of the depth of cut. The limiting depth of cut a_{lim} for turning can be provided as:

$$a_{lim} = -\frac{1}{2K_r Re(G(j\omega))} \tag{1}$$

where: K_r – cutting force coefficient, $Re(G(j\omega))$ – real part of the FRF $G(j\omega)$ determined for the compliant part of the machine tool system.

For slender shaft turning the FRF is evaluated for the workpiece, while for a boring process, where tools usually have long overhangs, FRF is determined at the tool tip. From Eq. 1 it can be seen that to determine the cutting depth limit (which should be positive) negative values of the real part of the FRF are required, as shown in Fig. 1a. The part marked "negative real" is directly used to determine stability lobes, by converting to rotational speeds using Eq. 2 and then replicating for subsequent positive integers k as shown in Fig. 1b.

$$N_c = \frac{60 \cdot f_c}{k}, \qquad \text{for } k = 1,2..,n \tag{2}$$

Variable f_c is the chatter frequency and k is a positive integer (representing the lobe number).

The stability lobes separate the stable and unstable machining area. Therefore, by selecting the appropriate spindle speed and cutting depth, chatter vibration can be avoided. The stability lobes presented in Fig. 1b require the FRF of the machine tool system and cutting force coefficient that describes the interaction between the workpiece (it is material) and the tool. In order to determine a stable cutting depth for specific spindle speed, the coefficients are evaluated experimentally for a specific set of the tool and the workpiece material. Omitting the influence of the coefficient does not allow for specifying the cutting depth limit, however it is still suitable for the selection of spindle speed. Although this solution does not guarantee full effectiveness in ensuring machining stability, the complex experimental procedure is omitted, making use of stability lobes more accessible for less advanced machining systems.

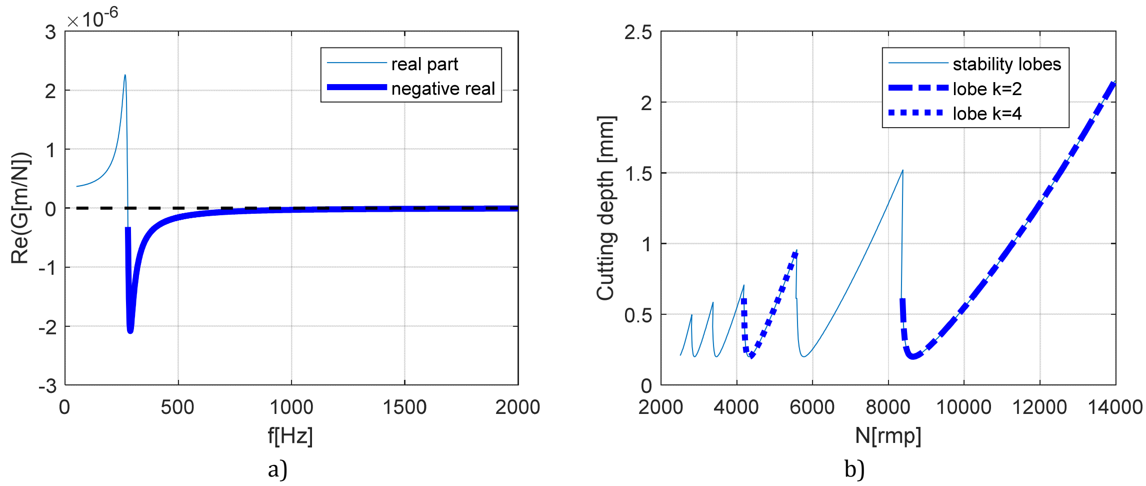


Fig. 1 a) Real part FRF of the machine tool system; b) Graphic representation of determining the stability lobes

2.2 Receptance coupling

The frequency response functions of the machine tool-workpiece system, needed for the stability lobes calculation, can be determined using the receptance coupling approach (RCA). To perform the synthesis of the dynamic properties of the coupled system, the FRFs for the selected points of its subassemblies are required. The developed procedure applies to the case in which slender shafts are machined. Therefore, this system consists of a lathe spindle with a three-jaw chuck (subassembly "1") and a workpiece, i.e. a rod (subassembly "2"). The components and their local coordinates are presented in Fig. 2a and the coupled system in Fig. 2b.

The modelled system consists of three points: “1” - point of the fixture spindle three-jaw chuck - workpiece, “2” a tool point which can be arbitrarily oriented along the axis of the workpiece, “3” point at the end of the workpiece. For turning, dynamic properties in the x direction have a major impact on chatter vibrations, therefore for the receptance coupling procedure the other directions have been neglected.

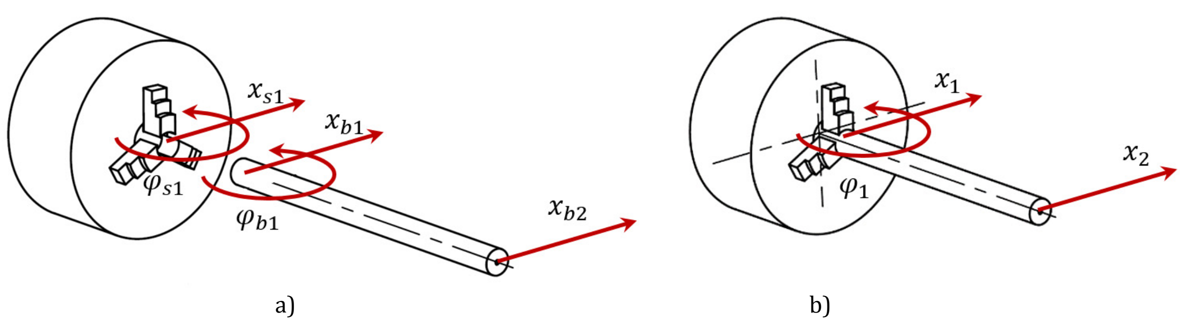


Fig. 2 a) The system subassemblies in the local coordinates; b) The coupled system

However, the use of receptance coupling for turning involves the difficulty of modelling the interaction between the workpiece and the three-jaw chuck. It is analogous to modelling machine (spindle and holder) tool joint for milling, for which the RCA method is most commonly used. Phenomena that occur when modelling such a fixture are presented, among others by Schmitz in [35]. To obtain correct calculation results, additional consideration of rotational degrees of freedom (RDOF) for the spindle - workpiece connection is required.

A Timoshenko beam model can be used in order to evaluate dynamic properties of the workpiece. First, information on geometry (diameter and length) and material properties are given, then boundary conditions are imposed (in this case "free – free") and finally the required FRFs can be calculated.

Matrix equations describing the dynamic properties of system components for receptance coupling procedure are given as follows:

$$\begin{bmatrix} x_{s1} \\ \varphi_{s1} \end{bmatrix} = \begin{bmatrix} H_{s11} & H_{s12} \\ H_{s21} & H_{s22} \end{bmatrix} \cdot \begin{bmatrix} F_{s1} \\ M_{s1} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} x_{b1} \\ \varphi_{b1} \\ x_{b2} \\ x_{b3} \end{bmatrix} = \begin{bmatrix} H_{b11} & H_{b12} & H_{b13} & H_{b14} \\ H_{b21} & H_{b22} & H_{b23} & H_{b24} \\ H_{b31} & H_{b32} & H_{b33} & H_{b34} \\ H_{b41} & H_{b42} & H_{b43} & H_{b44} \end{bmatrix} \cdot \begin{bmatrix} F_{b1} \\ M_{b1} \\ F_{b2} \\ F_{b3} \end{bmatrix} \tag{4}$$

where: x – the x direction translational displacement, φ rotation angle, H_s – spindle FRFs, H_b – workpiece FRFs, F – force, M – torque.

For the spindle, the translational FRF H_{s11} can be determined by impulse testing. However, the RCA also requires the rotational FRFs (H_{s12}, H_{s21}, and H_{s22}) and the experimental determination of these is troublesome. The methods provided for the experimental determination of RDOFs in practice turn out to be sensitive to measurement inaccuracies or have numerous limitations resulting from the fact that they were mainly developed for tool-holder joints in milling. The issue of experimental determination of rotational FRFs for lathe applications was explored by Jasiewicz and Powałka in [33] where the Extended Inverse Receptance Coupling (EIRC) procedure was presented. The method assumes the determination of the FRF of a spindle using the inverse receptance coupling. The translational transfer functions of the system spindle - rod are evaluated experimentally (by impact testing) and the system is decoupled so that the FRF of the subassembly, i.e., the spindle, can be obtained. Moreover, in order to increase the calculation accuracy, the number of measurement configurations has been extended. The EIRC method was used to determine spindle FRFs.

While having the transfer functions of the workpiece and the spindle, the RCA can be performed to evaluate the machine tool system dynamic properties. The relationships between the points of the system constitute boundary conditions and equilibrium of forces. Moreover, local coordinates (for separate subassemblies) are replaced by the global ones (for a coupled system):

$$\begin{cases} x_{S1} = x_{b1} = x_1 \\ \varphi_{s1} = \varphi_{b1} = \varphi_1 \end{cases}, \quad \begin{cases} F_{S1} + F_{b1} = F_1 \\ M_{s1} + M_{b1} = M_1 \end{cases} \tag{5}$$

By including boundary conditions and equilibrium of forces in the spindle (Eq. 3) and beam (Eq.4) matrices the coupled system matrix equation is obtained:

$$\begin{bmatrix} x_1 \\ \varphi_1 \\ x_2 \\ x_3 \end{bmatrix} = T \cdot \begin{bmatrix} H_{b11} & H_{b12} & H_{b13} & H_{b14} \\ H_{b21} & H_{b22} & H_{b23} & H_{b24} \\ H_{b31} & H_{b32} & H_{b33} & H_{b34} \\ H_{b41} & H_{b42} & H_{b43} & H_{b44} \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ M_1 \\ F_2 \\ F_3 \end{bmatrix} \tag{6}$$

In the matrix equation, Eq. 6, the dynamic properties of the coupled system are determined as the product of the matrix T and the matrix containing beam FRFs. The T matrix contains the spindle and beam FRFs and is given as:

$$T^{-1}=\begin{bmatrix} 1+\dfrac{H_{b11}H_{S22}-H_{b12}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & \dfrac{H_{b12}H_{S11}-H_{b11}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & 0 & 0 \\ \dfrac{H_{b21}H_{S22}-H_{b22}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & 1+\dfrac{H_{b22}H_{S11}-H_{b21}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & 0 & 0 \\ \dfrac{H_{b31}H_{S22}-H_{b32}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & \dfrac{H_{b32}H_{S11}-H_{b31}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & 1 & 0 \\ \dfrac{H_{b41}H_{S22}-H_{b42}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & \dfrac{H_{b42}H_{S11}-H_{b41}H_{S12}}{H_{S11}H_{S22}-H_{S12}H_{S21}} & 0 & 1 \end{bmatrix} \tag{7}$$

Using the RCA procedure presented, FRFs of the machine tool system are obtained, which are the basis for predicting system stability and thus determining technological parameters to avoid vibrations during the machining.

2.3 Proposed machining parameters selection system

The beginning of the production process using a CNC machine tool is usually the analysis of technical documentation, i.e., technical drawing. Then, based on experience and knowledge about machining technology, the tools to perform the machining are selected. Regardless of the system in which it is developed, the machining program consists of commands describing the geometry of the part, allowing the tool path to be calculated. In addition, the operation of machine tool systems is controlled (e.g. spindle on/off, coolant activation, tool change), but also machining parameters must be selected. For turning, these include the feed, the cutting depth and the spindle rotational speed (or cutting speed). The manufacturers of the cutting inserts usually provide the recommended ranges to facilitate the selection of optimal parameters. However, this selection does not respect the dynamic properties of the machine tool-workpiece system and while machining of compliant parts, a small change in parameters can significantly change the cutting conditions i.e., affect whether the machining will be stable or whether vibration will occur. As an example, turning parts with a 30 mm diameter with a tool for which the manufacturer recommends the cutting speed from 335 to 450 m/min gives a spindle rotational speed in the range of 3350-4770 rpm. For a non-susceptible part (low length – diameter ratio), choosing a higher cutting speed will only mean higher machining efficiency with lower tool life, while for lower speeds, the cutting process will take longer, but more parts can be machined with the same tool insert. However, for the parts with high compliance, where the risk of chatter vibration occurrence during the cutting is particularly high, this issue becomes more complex. For such parts, it is justified to determine the stability lobes, representing the area of stable and unstable machining, as shown in Fig. 3.

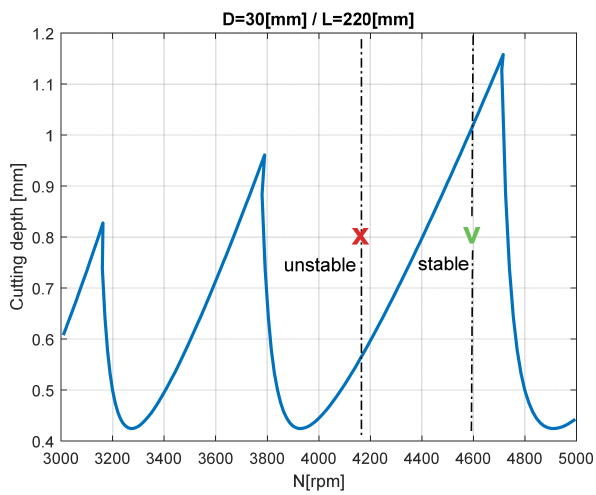


Fig. 3 Selection of the spindle rotational speed on stability lobes diagram

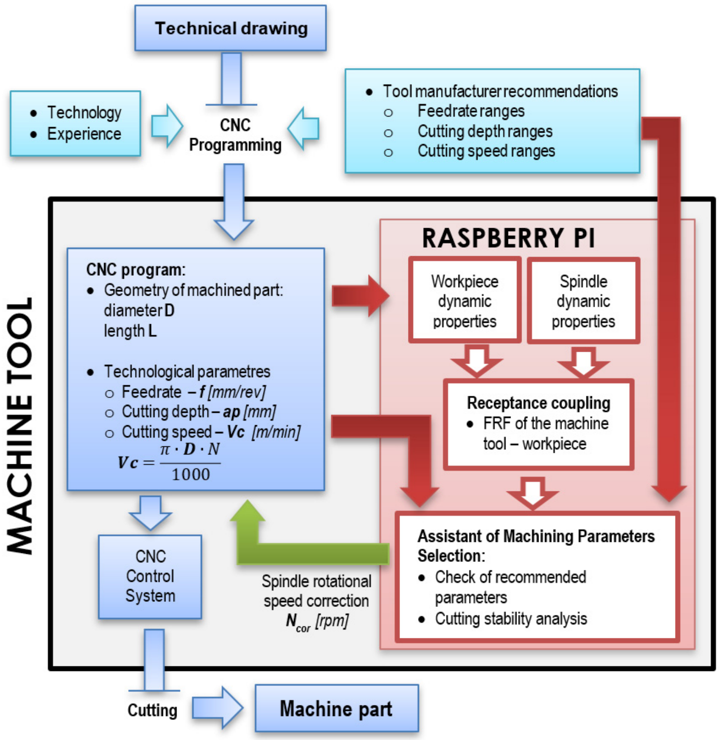


Fig. 4 The concept of machining parameters selection system

When analyzing the stability lobes, it can be seen that at a given cutting depth, for some spindle rotational speeds from the recommended speeds range, the machining will be stable, while for others the chatter vibration will occur. However, in practice, stability lobes are rarely determined before machining because they require an impact test to be carried out for a specific workpiece mounted in the spindle chuck. This can be done using the specialized measurement equipment, software and requires highly qualified staff. For these reasons, this solution is unprofitable for most small and medium-sized manufacturing companies. The proposed approach is a low-cost solution. Importantly, the system is integrated with the CNC system of the machine tool, which does not require performing any calculations on an external device. The concept of the system operation is presented in the algorithm in Fig. 4.

The machining program is developed in the same way as for standard machining, except that additionally, the cutting speed range must be specified. This may be the range provided by the tool insert manufacturer or resulting from the programmers experience. In order to determine the properties of the machine tool-workpiece system using RCA, it is necessary to have FRFs matrices of workpiece and spindle as the input. The spindle properties are determined using the EIRC method at the stage of system installation at the machine tool and the FRFs matrix is saved in the single-board computer (Raspberry Pi 4) memory. The dynamic properties of the workpiece are determined using the Timoshenko beam model with defined diameter and length. As presented earlier in section 2.1, the influence of the cutting force coefficient (related to material properties) is neglected, which in practice means that only "stable" rotational speeds of the spindle are sought. The cutting speed preselected in the machining program is compared with a set of "stable" spindle speeds and as a result, the system indicates the nearest spindle rotational speed that can contribute to chatter suppression.

In the presented form, the method is dedicated for turning and can be useful when machining slender workpieces. However, the concept of the machining parameters selection system can be also applied to milling operations. The receptance coupling method is commonly used to determine the dynamic properties of the spindle-holder -tool system. However, it should be emphasized that then the use of the system would be justified for machining with slender tools, which, due to their geometry, could be analytically modeled as a beam with a circular cross-section. For milling, there are also cases where thin-walled workpieces are machined. In these cases, the application of the presented system will not be helpful.

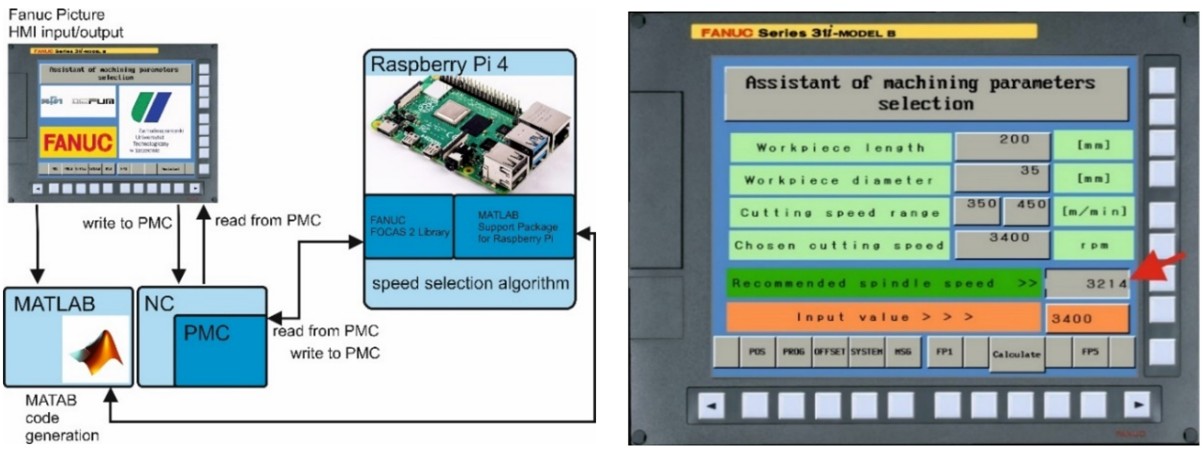
3. Results and discussion

3.1 Implementation of the system in the CNC control

The machining process assistant has been integrated with the FANUC CNC 31i model B control system. The FANUC control system is a part of a medium size lathe AFM TAE 35 "Hanka" manufactured by “Andrychowska Fabryka Maszyn DEFUM S.A”. The speed selection algorithm has been implemented in a single-board computer Raspberry Pi 4B with Raspbian OS. Raspbian is an open-source operating system optimized for the SoC Raspberry Pi hardware. Raspbian includes a set of basic programs and utilities that allows the usage of the Raspberry Pi. MATLAB Coder was used to generating and deploying the C/C++ code on Raspberry Pi. Communication between RPi 4 and NC/PMC controller is implemented over the Ethernet. On the CNC control side, the Ethernet communication is implemented by the socket communication (TCP/IP) with FANUC Ethernet Board with the "Embedded Ethernet function". A diagram of the communication between the system components, with the libraries and software used, is shown in Fig. 5a.

The first step to integrating the developed algorithm into the CNC system was to develop an HMI user interface. The FANUC Picture software was used for this purpose. This software allows integrators to create customized operator screens and implement complex machining functions. Created screens are compiled and saved in the CNC Flash-ROM (FROM) memory. Properly prepared and uploaded compiled code is rendered by the CNC main processor on an HMI LCD screen. The prepared assistant main screen is shown in Fig. 5b.

After the machine is switched on, the start-up screen appears on the operator panel. The main screen allows the operator to switch directly to the assistant's settings or other machine functions. When the screen appears, the machining parameter fields are empty. The following parameters (necessary for the calculation) are required from the operator to use the system: workpiece length, workpiece diameter, cutting speed range, chosen cutting speed. Then entered parameters are saved in PMC memory in R (relay) data area. The next step necessary to integrate the proposed solution into the machine was to prepare the Raspberry Pi 4 single-board computer. First, using MATLAB Coder software, the MATALB code of the developed algorithm for RPi 4 was generated. That code can be deployed and run standalone on the Raspberry Pi prepared by MATLAB Support Package for Raspberry Pi Hardware creator. The pseudo-code of the algorithm is given below.



a) b)

Fig. 5 a) Operating diagram of the integrated system for chatter suppression; b) Operator screen of the integrated system for chatter suppression

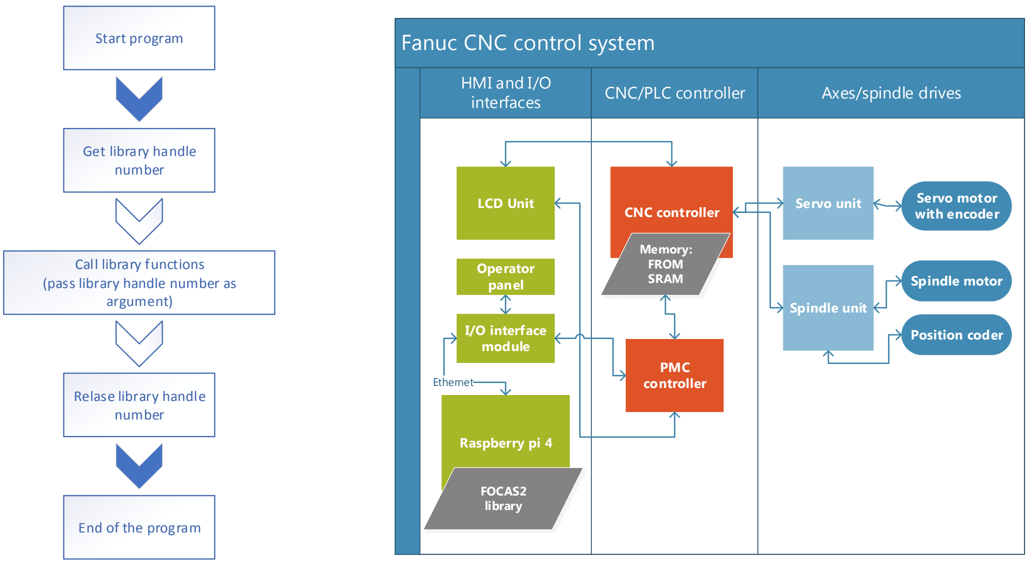
Table 1 Algorithm of spindle rotational speed selection pseudocode

Algorithm of spindle rotational speed selection
Input: $D, L, V_{c\,range}, V_{c\,select}$
Output: N_{cor}
Read input data form CNC
Calculate beam FRFs matrix H_b
Load spindle FRFs matrix H_s
Synthesize FRFs of the coupled system using RCA
Determine the stability lobes and select stable speeds N_{stab}
Transform cutting speeds V_c to N rotational speeds
Find $N_{stab} \in N_{range}$ closest to N_{select} and assign as N_{cor}
Send N_{cor} to NC/PMC

D – workpiece diameter, L – workpiece length, $V_{c\,range}/N_{range}$ – cutting speed/spindle rotational speed range, $V_{c\,select}/\ N_{select}$ – cutting speed/spindle rotational speed selected in machining program, N_{stab} – stable spindle rotational speeds, N_{cor} – recommended spindle rotational speed

FANUC FOCAS2 for ARM libraries were used to read/write values of variables from/to R registers of the PMC controller. The use of these libraries allows creating custom programs and cycles that are not available by default in the CNC system. FOCAS2 libraries provide direct access to the variables, parameters, registers in NC/PCM memory areas, control of the machine axis, perform complex calculations and connecting external devices. Establishing communication between the CNC controller and SoC requires creating the library handle and the TCP/IP connection by passing a CNC's IP address parameter to the cnc_allclibhndl3 function. Acquired library handle number must be known until the application program terminates. The actual instance handle number is required as an argument in every call CNC/PMC Data window library function.

The following functions were used to read and write values using RPi 4 via Ethernet connection: cnc_rdunsolicprm2 (to read parameters), cnc_wrunsolicprm2 (to write parameters). It is necessary to execute cnc_wrunsolicprm2 and make the parameter effective before reading the parameters. The outline of the processing sequence of a FOCAS2 application is shown on Fig. 6a. In the prototype system phase it was necessary to use the NCGuide CNC simulator. FANUC NCGuide is a software for simulating real CNC machine (G-code and PLC/PMC code). It allows for real programming, operation, and maintenance environment without using a production machine tool. For a better understanding overview of the complete control system architecture with connections is presented in Fig. 6b.



a) b)

Fig. 6 a) FOCAS2 application processing sequence; b) Structure of Fanuc CNC control system

At the prototype stage of the solution, all necessary parameters must be entered to calculate the recommended settings. In the next version of the system, the number of parameters required to enter will be reduced. A special algorithm will be prepared which will download cutting speed and the diameter of the workpiece information from G-code. The main advantage of the developed solution is that it: does not change the existing system functionality, increases user convenience by limiting the amount of data entered, additional equipment allowing to perform calculations is fully integrated with the CNC system.

3.2 Experimental tests

In this subsection, the experimental test results were presented to validate the proposed solution. The system was integrated into a AFM TAE35 CNC lathe on which cutting tests on the slender workpiece were carried out. The workpiece was a circular cross section rod of a diameter of 40 mm, length 250 mm and the material was a machining steel 1.0715 (11SMn30). The SVJCL 2020-16 cutting tool was used, equipped with VCMT 160402-SM cutting insert.

The initial step of the procedure was to determine the dynamic properties of the machine tool-workpiece system using the RCA. For the analysis of machining stability, the most significant is the first vibration mode, which for the selected system was at a frequency of 223 Hz. Then, the stability lobes diagram for the selected system was evaluated, as given in Fig. 7. The cutting test plan assumed the machining of two 10mm long sections at the end of the workpiece. Due to the lack of support with the tailstock, the rigidity of the system is the lowest at the end, and therefore the risk of chatter vibrations is the greatest. In order to set the same cutting depth for both sections, without passing through the machined surface, "Section 1" (closer to the face) has been pre-machined. The effectiveness of the proposed procedure consisted of machining Section 1, with the spindle rotational speed set arbitrarily, whereas for "Section 2" the spindle speed has been corrected using the presented machining parameters selection system. For both sections, the cutting depth and the feed value remained unchanged. Fig. 8 presents the results of one of the performed experiments.

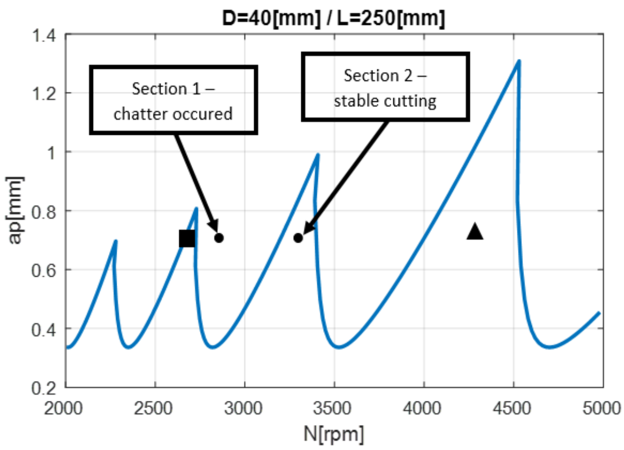


Fig. 7 The Stability lobes for the selected machine tool - workpiece system

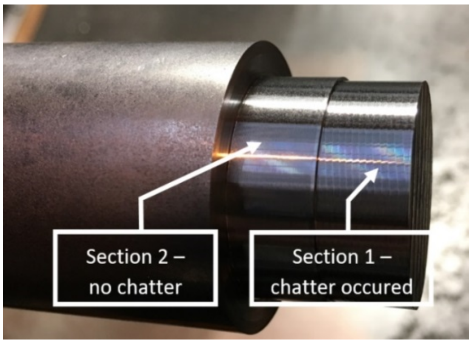


Fig. 8 Experimental test result – machined surfaces

For the “Section 1”, the selected cutting speed was 290 m/min, which for the 32 mm diameter gives a rotational speed of approx. 2800 rpm. The cutting depth a_p was 0.7 mm and feed per revolution 0.05 mm. The analysis of the stability lobes diagram in Fig. 9 gives that for the machine tool-workpiece system, the selection of this rotational spindle speed may lead to chatter vibration occurrence during the machining. However, this cannot be stated without the stability lobes for the workpiece setting, normally not determined in industrial applications. Thus, despite the selection of the cutting speed from the range given by the cutting insert producer, the chatter marks appeared on the machined surface in “Section 1”. The cutting in “Section 2” was performed with the spindle rotational speed proposed by the machining parameters selection system. Setting the same feedrate and cutting depth as for “Section 1”, but correction of the spindle rotational speed to 3250 rpm, allowed to obtain a stable, chatter-free machining process. As can be seen in Fig. 7, in the presented rotational speed range, other stable speeds can be selected for determined cutting depth. However, by choosing a speed of 4200 rpm (pointed as triangle), the cutting speed is outside the speed range proposed by the tool manufacturer, which may result in accelerated tool wear or even cutting-edge damage. For a lower speed, e.g. 2600 rpm (pointed as a square), the machining performance is lower, and there is an increased risk of going outside the stable machining area. At the surface machined with the corrected spindle rotational speed no chatter marks were observed, which indicates that the manufacturing process could be successfully continued.

4. Conclusion

The paper presents the issue of selecting the cutting parameters for compliant workpieces turning. The selection of these parameters is practically based on ranges provided by the cutting tools producers or on the experience of the programmer. In most cases, this approach is sufficient and only the manufacturing efficiency and tool life depend on the choice made. However, the selection of rotational speed and cutting depth is particularly important for compliant parts machining, as it can affect the occurrence of unwanted chatter vibrations. The algorithm implemented on a single board computer integrated into the CNC control system presented in the article allows supporting the task of selecting these parameters. The determination of machining stability is based on the analysis of the frequency response function of the workpiece mounted in the lathe. A significant advantage of the presented system compared to other research works on turning stability is the omission of impulse tests by application of the receptance coupling approach (most commonly used for milling). The dynamic properties of the machine tool-workpiece system determined by this method are a substantial part of the standard stability lobes determination procedure. However, in order to simplify the procedure for selecting technological parameters, the influence of the cutting force factor was omitted. As a result, it only allows searching for the "stable rotational speeds” without setting a cutting depth limit that may be considered a drawback of the system. Nevertheless, in many cases, this simplification proves to be sufficient and may be useful in industrial practice while selecting the machining parameters. An important advantage of the proposed solution is integration with the CNC control system. The system is operated from the operator panel and only calculations are carried out on an external single board computer. This solution does not require an independent computer station outside the machine tool and therefore is a low-cost solution. Moreover, what is particularly important from a practical point of view, it can be installed both on brand new and already used machine tools already working in the industry. Due to the use of a single-board computer Raspberry Pi, the system is not a closed solution and new options and improvements can easily be introduced. Although the system presented in the article refers to turning, in some applications, it can also be adapted to milling. The following studies will concern, among others, extending the stability analysis with cutting depth and introducing the system interface improvements.

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