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THE INFLUENCE OF SOME FACTORS ON THE VIBRATIONS GENERATED BY WOODWORKING SPINDLE MOULDER MACHINE WHEN PROCESSING SPECIMENS FROM BEECH WOOD

Pavlin Vitchev – Zhivko Gochev – Georgi Vukov

ABSTRACT

The general dynamic behavior of a woodworking spindle moulder machine, determined by the mean square value of the vibration speed (v_{rms}, mm·s^{-1}) measured on the shaft bearings is investigated in the study. Among the measured factors, the cutting speed (V_c) has the greatest influence on the vibration intensity, followed by the feed rate (V_f) and the depth of milling (h). The results show that the vibration velocity varies in the range from 2 to 8 mm·s^{-1} at the different values of the variable factors. On the basis of this results, with regard to the magnitude of the overall vibrations generated by the used milling machine in processing specimens of beech wood (*Fagus sylvatica* L.), the following optimum values are recommended: cutting speed $V_c \in (34 \div 40)$ m·s^{-1}; feed speed V_f up to 4 m·min^{-1}; cutting depth h up to 8 mm. In cases when h>8 mm, the recommended feed speed is V_f < 3.5 m·min^{-1}. Based on the presented graphical relationships, the optimum values of the studied factors can be determined in order to reduce the overall vibration of the machine, which is an important prerequisite for the good work of the cutting tool and for improving the quality of the machined surfaces during processing the specimens from beech wood.

Key words: woodworking milling machine, milling, vibration severity, vibration speed.

INTRODUCTION

The dynamic behaviour of each woodworking milling machine is of great importance for its operational reliability as well as for reliable operation and for maintaining the geometrical accuracy of the linear and angular parameters of the woodworking tools.

The magnitude of vibrations in woodworking machines affects the accuracy of specimens' processing and the roughness of their surfaces (KAVALOV *et al*. 2014, KAVALOV *et al*. 2015). Increased vibrations are a prerequisite for reducing the quality of processing.

The dynamic behaviour is characterized by the magnitude of the machine's general vibrations, the change of which can be the result of various structural and technological parameters, as well as depending on the characteristics of the materials being processed.

To estimate the vibration of a machine, it is agreed to use the maximum vibration value recorded at one of the measuring points where the measurements were taken. According to the regulatory guidelines this value is determined as vibration severity (ISO 10816-1)

The increased vibration intensity of a machine may result from poor balancing of the rotating elements as well as misalignment of the belt pulleys in the belt drive (VUKOV 2008).

The use of cutting tools balanced with insufficient precision also causes a change in the overall dynamic behaviour of the entire machine (DINKOV *et al*. 1990, YAITSKOV *et al*. 2019). Another prerequisite for increasing the overall vibration of the machine is based on the fact that modern woodworking machines operate at high rotational speeds of their cutting tools (BRUEL & KJAER VIBRO 2011, VUKOV *et al.* 2014, VAN *et al.*2018). Further, in the cutting process there are interactions between the cutting tool and the workpiece which, depending on the cutting speed and the feed rate, lead to formation of cutting forces. When the above mentioned factors are increased, an increase in the vibration energy is observed as well (ISKRA *et al*. 2005, KETURAKIS *et al*. 2007, ZHANG *et al.* 2011, GOCHEV *et al*. 2017a, GOCHEV *et al*. 2017b, YAITSKOV *et al.* 2019, GORSKI *et al.* 2019, VAN *et al.* 2020, CHUNMEI *et al.* 2020). Based on one of our previous studies (GOCHEV *et al*. 2017A) we showed that the surface quality of specimens from white pine (*Pinus Sylvestris* L.) wood was higher at cutting speed from 40 $m \cdot s^{-1}$ to 45 $m \cdot s^{-1}$, and at feed rates up to 5 $m \cdot min^{-1}$ with a thickness of the specimens of up to 8 mm (GOCHEV *et al*. 2017a).

Another factor that may influence the vibrations' intensity is the type of workpiece material. For example, processing of specimens from oak and fir wood is characterized with uneven intensity of the vibrations, while the vibrations generated during processing of beech wood specimens are with a constant amplitude. Those differences are explained by the presence of early and late wood in the oak and fir trees and the homogenous structure of the beech wood (LUSTUN and LUCACI 2010).

The aim of the current study was to investigate the changes in the magnitude of the general vibrations generated by the used woodworking spindle moulder machine under cutting mode with different cutting speed (V_c), feed speed (V_f) and depth of cut (h) while processing specimens from beech (*Fagus sylvatica* L.) wood. In addition, based on the evaluated vibration levels under this experiment, optical milling parameters are recommended for this particular machine.

METHODOLOGY

The experiments were carried out using woodworking spindle moulder machine, type T1002S (ZMM "Stomana" GmbH, Bulgaria) (Fig. 1). The machine was equipped with a two-speed three-phase electric motor with power 3.2/4.0 kW, which provides the following rotating speed of the spindle: 3000, 4000, 5000, 6000, 8000 and 10000 rpm through a belt drive.

Fig. 1 Woodworking spindle moulder machine, type T1002S – general view.

The machine is also equipped with a roll feeder, driven by self-powered electric motor which could ensure feeding speed of the processed material from 3.5 to 32 m·min^{-1}. Under the cutting mode of the machine, a monolithic cutting tool was used with technical characteristics presented in Table 1, where D is the diameter of the cutter head, d – diameter of the hole, B – milling width, β – sharpness angle, γ – hook angle, z – number of teeth. The cutting tool was dynamically balanced with the necessary permissible residual unbalances allowed at rotational speed up to n_1 = 8000 min^{-1}.

Fig. 2 General view of the used cutter head.

Tab. 1 Technical characteristics of the used cutter head.

D mm	***d*** mm	***B*** mm	**β** °	**γ** °	***z*** No	n_1 min^{-1}	**Material of the teeth**
140	30	12	58	20	6	8000	Sintered tungsten carbide – cobalt, (HM-M40)

The workpiece is from beech wood (*Fagus sylvatica* L.) with density ρ = 690 kg·m^{-1}, moisture W = 11 % and dimensions 1000 × 50 × 50 mm.

The experiments have been carried out at the three possible rotational speeds of the cutting tool (n), namely 4000, 6000 and 8000 rpm (min^{-1}). The cutting speed (V_c) varies depending on the speed of rotation in accordance with the following equation (GOCHEV 2018)

$$V_c = \pi.D.n,\ [\mathrm{m{\cdot}s^{-1}}], \tag{1}$$

where:
D – diameter of the cutting tool, *m*;
n – rotation frequency of the cutting tool, s^{-1}.

In the current study, the overall dynamic behaviour of the milling machine was monitored based on the variation of the vibration magnitude measured on the non-rotating parts of the machine under cutting mode. The effect of the cutting speed (V_c) or the rotational frequency of the cutting tool, the feed rate (V_f) and the thickness of the cutting depth (h) were monitored.

In the course of the study, the three variables were measured at three levels which are presented in explicit and coded form in Table 2.

The measurements were performed in accordance with a preliminary designed matrix B_3 for three factorial experiment plan of G. Box of second order. In addition to the experiments, according to the requirements of the B_3 matrix for each individual experiment, five additional experiments are carried out under conditions corresponding to the middle of the factor space, i.e. $x_1 = 0$, $x_2 = 0$ and $x_3 = 0$. On the basis of these measurements the error variations Sg^2 have been determined. For the statistical analysis an average value from three independent measurements for each combination of factors in the experimental matrix have been used. The data were statistically analysed by a specialized software Q-StatLab.5.

Tab. 2 Values of the variable factors V_c, V_f and h.

Variables	Minimal value		Medium value		Maximal value	
	Expl.	Coded	Expl.	Coded	Expl.	Coded
Cutting speed $V_c = x_1$ [m·s^{-1}]	29	–1	44	0	59	1
Feed speed $V_f = x_2$ [m·min^{-1}]	3.5	–1	7	0	10.5	1
Cutting depth $h = x_3$ [mm]	4	–1	8	0	12	1

The variations in the magnitude of the vibrations, generated by the tested machine and their relationship to the evaluated variables were assessed by measuring the root mean square value of vibration velocity (v_{rms}, mm·s^{-1}) at different working modes of the machine. The measurements were performed at four measuring points located on two bearing housings of the spindle of the machine (two measurement points on each bearing housing). The measurement points on each bearing housing are located mutually perpendicular – 2 of them radial (*y* and *x*) and 1 axial (*z*) to the axis of the spindle of the machine (Fig. 3).

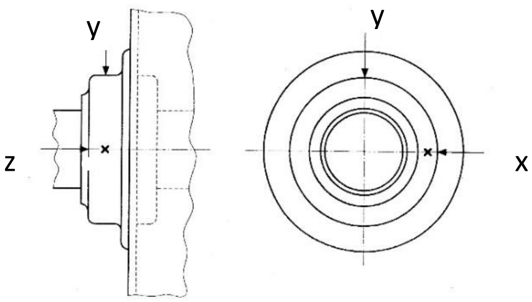

Fig. 3 Measurement points on one bearing housing.

In the current study, the measurement points are defined as follows:

- For the bearing housing located in proximity to the driven belt pulley, hereinafter referred to as "lower bearing housing", the measurement points are indicated by D_x – in the direction parallel to the feed direction and D_y – in direction perpendicular to the feed direction;
- For the bearing housing located in proximity to the working top of the machine and the cutting tool, hereinafter referred to as "upper bearing housing", the measurement points are indicated by G_x – in direction parallel to the feed direction and G_y – in direction perpendicular to the feed direction.

The requirements given in BDS ISO 10816-1 and ISO 2041 were strictly followed throughout the experiments. For the measurement of the vibration velocity a vibration meter, model *Vibrotest* 60 (Schenck, Germany) has been used. The vibration meter is equipped with an acceleration sensor, model AS-065 (*Bruel & Kjaer Vibro*) (Fig. 4).

Fig. 4 General view of the vibration meter, model Vibrotest 60, equipped with acceleration sensor.

A magnet is used for fixing the sensor to the bearing housings of the predetermined measurement points. To ensure the good fixation, the bearing housings have been cleaned out of paint, dust and other contaminants.

RESULTS AND DISCUSSION

The obtained results prove the effect of the investigated factors on the dynamic behaviour of the machine, which is confirmed by the results of other authors studying a similar type of machine (KOVACHEV *et al.* 2018a, KOVACHEV *et al.* 2018b, VAN *et al.* 2018, CHUNMEI *et al.* 2020), who observe a similar trend in the variation of the magnitude of the vibrations as a result of the change of the variable factors characterizing the cutting process.

The results obtained from the experimental study clearly show significantly higher vibration values at measurement points G_x and G_y which are located on the bearing housing in proximity of the cutting tool (upper bearing housing) compared to the vibrations measured at points D_x and D_y (lower bearing housing). Therefore, under the cutting mode conditions the dynamic behaviour of the machine was investigated and analysed based on the vibrations measured at points G_x and G_y.

After applying the method of regression analysis and statistical analysis of the data (by specialized software QStatLab.5) the regression equations (2) and (3) have been derived. These equations are used to predict the vibration magnitude in the range of the investigated factors at the measurement points G_x and G_y, as follows:

Regression equation for measurement point G_x;

$$\hat{y}=2{,}211+2{,}488x_1+0{,}178x_2+0{,}271x_3+3{,}424x_1^2-0{,}124x_2^2-0{,}049x_3^2-0{,}351x_1.x_2+0{,}169x_2.x_3-0{,}161x_1.x_3 \quad (2)$$

Regression equation for measurement point G_y;

$$\hat{y}=2{,}231+1{,}441x_1+0{,}086x_2+0{,}045x_3+1{,}328x_1^2-0{,}083x_2^2-0{,}018x_3^2-0{,}163x_1.x_2+0{,}233x_2.x_3-0{,}373x_1.x_3 \quad (3)$$

where:
x_1 – cutting speed, coded;
x_2 – feed speed, coded;
x_3 – cutting depth, coded.

The calculated correlation coefficients for the two derived regression equations are: for equation (2) – R^2 = 0.99; for equation (3) – R^2 = 0.98.

From the values of the F-distribution and the abulated coefficient F_T it was found that for the three regression equations the Fisher criteria for the adequacy of the model, namely $F \leq F_T$ are fulfilled, therefore, the results could be further analysed.

From the values of the regression coefficients in front of the variable factors, for both regression equations, it can be concluded that the greatest influence on the magnitude of the vibrations had the cutting speed V_c (with regression coefficients 2.488 and 1.441), respectively the rotational frequency of the cutting tool.

From equation (1) it is visible that at one and the same cutting diameter D, the cutting speed increases with an increase of the rotational speed of the cutting tool n. The increase in the cutting speed V_c results in an increase vibration velocity v. The other two measured factors exerted almost equal influence on the vibration velocity. However, in the measurement point G_x a slightly higher influence had the thickness of the output layer (with regression coefficient 0.271), while in measurement point G_y the feed speed (with regression coefficient 0.086) exerted a bit higher influence.

The changes in the vibration speed at measurement points G_x and G_y in relation to the cutting speed are presented in Figures 5 and 6.

From the results in the Fig. 5 is visible that with an increase in the cutting speed V_c from 29 m·s^{-1} to 36 m·s^{-1} the vibrations magnitude decreased at all three assessed feed speeds V_f. However, when the cutting speed V_c increased above 44 m·s^{-1}, the vibration's magnitude increased. A distinct difference in the values of the vibration velocity for the three feed speed was observed at cutting speed ranged from 25 m·s^{-1} to 45 m·s^{-1}.

At the lowest speed feed V_f = 3.5 m·min^{-1} the vibrations' velocity is higher when compared to the higher feed speed of V_f = 7 and V_f = 10.5 m·min^{-1}.

It is worth mentioning that when the cutting speed is above 50 m·s^{-1}, the vibrations' magnitude is equal at the three feed speeds and increased significantly by increasing the feed speed. The maximal value of the vibration velocity of v_{rms} = 7.74 mm·s^{-1} was reached at V = 59 m·s^{-1}.

Regarding the vibrations' magnitude, measured at points G_x (Fig. 5) and G_y (Fig. 6), it could be concluded that the measured values were lower at point G_y, where the maximal value of v_{rms} = 5.16 mm·s^{-1} was measured at maximal tested cutting speed of V_c = 59 m·s^{-1}.

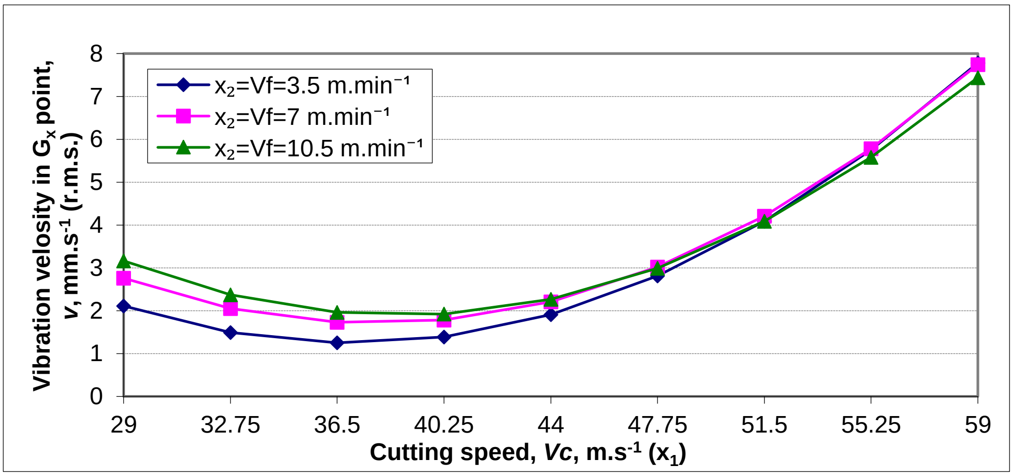

Fig. 5 Assessment of vibration velocity *v* at measurement point G_x in relation to the cutting speed V_c at different feed speed V_f.

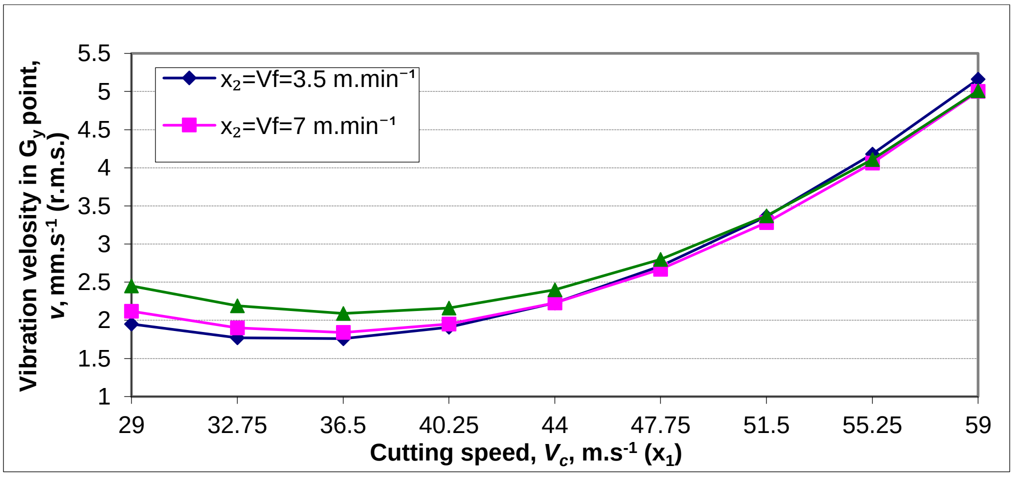

Fig. 6 Assessment of vibration velocity *v* at measurement point G_y in relation to the cutting speed V_c at different feed speed V_f.

The changes in the vibration velocity, evaluated at the measurement point G_y, in relation to the cutting speed at three different values of the cutting thickness h are presented in Fig 7. This graph, as well as the previous ones, shows a slight decrease in the magnitude of the vibrations in the lower limit of the investigated cutting speed range V_c. A distinct difference in the value of vibration velocity depending on the thickness of the out-cut layer is observed in the cutting speed interval from 29 m.s^{-1} to 40 m·s^{-1}. With an increase of the cutting speed above 45 m.s^{-1}, the intensity of the vibrations increases as well.

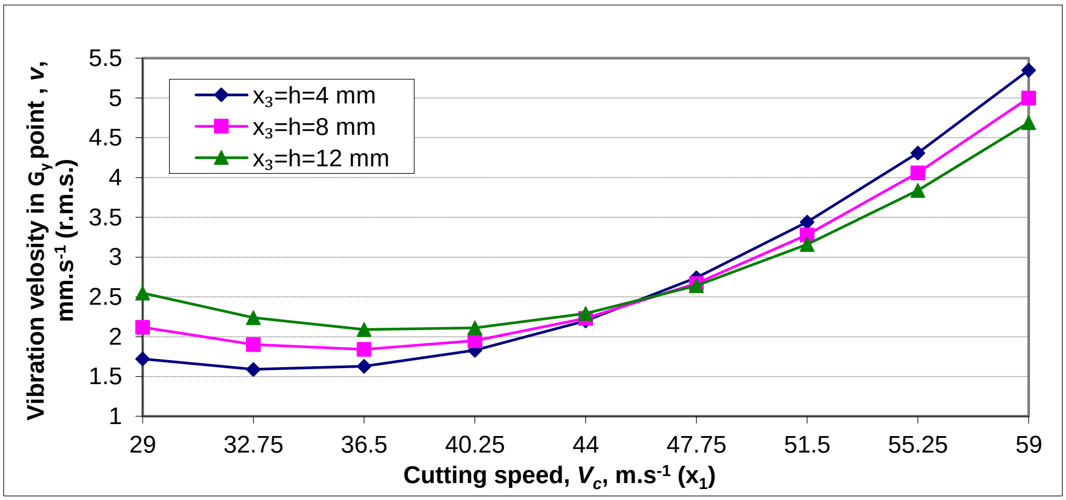

Fig. 7 Changes in the vibration velocity *v* at measurement point G_y in relation to the cutting speed V_c at different out-cut layers *h*.

For the graphical representation of the changes in vibrations' magnitude in relation to the feed speed V_f, at three different thicknesses of the layer h, the values of the vibration velocity v, measured at point G_x have been used (Fig. 8).

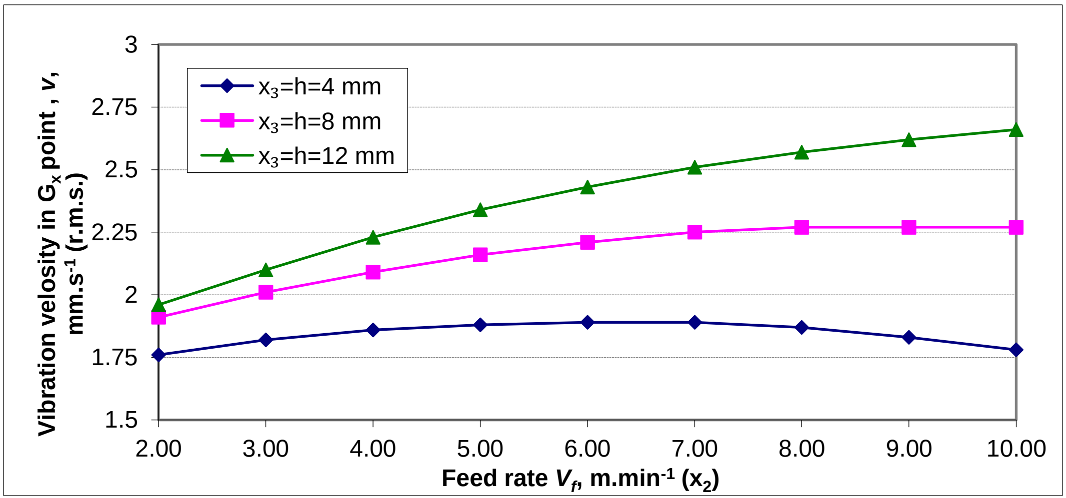

Fig. 8 Changes in vibration velocity *v* at measurement point G_x in relation to the feed speed V_f at different thicknesses of the out-cut layer *h*.

It can be seen from the graph that with an increase of the thickness of the out-cut layer h, the magnitude of the vibrations increase at one and the same speed feed V_f. A slight difference in the vibration velocity between three thicknesses of the out-cut layer h was observed at feed speed ranging from 2 to 4 m·min^{-1}. With an increase of the feed speed V_f above 6 m·min^{-1}, however, the difference increases and it is more visible between h = 4 and h = 8 mm, when compared to h = 8 mm and h = 12 mm.

CONCLUSIONS

Based on the result of our study could be concluded that for this type of milling machines, higher vibration velocity v was observed at the upper bearing housing of the main shaft of the machine which could be explained with the overhanging shaft. Mounting of the cutting tool additionally changes the weight of the spindle in its upper edge, which could also be regarded as a reason for the increased vibrations, measure at the upper bearing housing of the machine in comparison to those measured at the lower bearing housing.

The results obtained under the conditions of this study confirmed the role of the evaluated factors on the overall vibrations, generated by the used milling machine. The highest influence on the increased magnitude of the vibrations exerted the cutting speed V_c, followed by the feed speed V_f and the cutting depth h.

On the basis of this results with regard to the magnitude of the overall vibrations, generated by the used milling machine in processing specimens of beech wood (*Fagus sylvatica* L.), the following optimal values are recommended: cutting speed $V_c \in (34 \div 40)$ m·s^{-1}; feed speed V_f up to 4 m·min^{-1}; cutting depth h up to 8 mm. In cases when h>8 mm, the recommended feed speed is V_f < 3.5 m·min^{-1}.

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AUTHORS' ADDRESSES

Chief Assist. Prof. Pavlin Vitchev, PhD
Prof. Zhivko Gochev, PhD
Prof. Georgi Vukov, PhD
University of Forestry
Faculty of Forest Industry
10 Kliment Ohridski Blvd.
1797 Sofia, Bulgaria
p_vitchev@ltu.bg
zhivko.g@ltu.bg
givukov@ltu.bg