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INFLUENCE OF FEED RATE ON THE DYNAMIC PROPERTIES OF THIN-WALLED PART DURING END-MILLING

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Abstract. *When selecting cutting modes for end-milling of thin-walled parts from hard-to-machine materials, their influence on machining stability must be considered. To do this, it is necessary to understand the types of vibrations that operate and the conditions under which they arise. Research has shown that different types of vibrations operate sequentially during cutting and only for a certain of time. During end-milling, forced and accompanying free oscillations operates due to the short duration of cutting. Their influence on the stability of the cutting process depends on the speed zone in which the milling takes place. The most unfavorable is the third speed zone of vibrations, where accompanying free vibrations of high intensity occur. Cutting speeds for machining parts from hard-to-machine materials fall precisely within this zone. The intensity of vibrations is influenced by the dynamic properties of the part. During end-milling of thin-walled parts, these properties are characterized by the amplitude and frequency of accompanying free vibrations, which exceed the natural frequency of the part's free vibrations. In other words, cutting modes alter the dynamic properties of the part. Some researchers focus on utilizing the damping properties of the feed. Therefore, the aim of this paper was to determine how the feed affects the dynamic properties of the part during cutting. A universal stand was used for the investigation, which allows for the creation of various dynamic characteristics of the processed sample and recording its motion laws during milling on an oscillogram. The research results showed that the feed, as an element of cutting modes, influences the dynamic properties of the part during cutting. It creates a variable layer that is being cut. Therefore, during the cutting time, the frequency and amplitude of accompanying free vibrations change during both up- and down milling. The feed affects the dynamic stiffness. Increasing the feed increases the dynamic stiffness of the part. This leads to a reduction in the amplitude of accompanying free vibrations during milling in the third speed zone of vibrations. The results presented in the article have practical significance for technologists in the aviation manufacturing industry. They help to better understand the physical processes occurring during milling and develop optimal processing strategies for thin-walled parts, which have high requirements for dimensional accuracy and surface quality.*

Keywords: *milling; milling cutter; thin-walled part; feed rate per tooth; oscillogram; accompanying free oscillations.*

1. INTRODUCTION

Thin-walled components, widely used in the construction of aviation products, attract special attention from technologists due to the close relationship between cutting conditions and high-intensity vibrations that occur during machining and affect its productivity, tool stability, dimensional accuracy, and surface quality [1].

To establish favorable cutting conditions, petal diagrams of stability [2–4] are utilized. Additionally, the distribution of vibrations across zones, depending on the ratio between the natural frequency of the component's vibrations and the frequency of forced vibrations [5, 6], allows for the analysis of milling conditions prior to processing, and also evaluate surface roughness [7, 8].

In some cases, the obtained results do not match expectations due to uncertainties regarding vibrations embedded in the calculations [9–13]. This is due to the fact that the pattern of oscillations and their dependence on cutting time is not taken into account. Studies [14] have shown that the following sequence of oscillations is observed during cutting. When the tool is plunged, forced vibrations appear. The accompanying free oscillations (AFO) are superimposed on them [14], which persist for several milliseconds before damping out. Then the system adjusts and steady-state self-oscillations occur. This oscillation sequence occurs during turning or face milling when the cutting time is long. However, during end milling of thin-walled components, the intermittent nature of cutting results in cutting times measured in a few milliseconds. This affects the fact that only forced oscillations are effective, which are imposed by the AFO. It is their intensity that most significantly influences the formation of the machined surface. It is worth noting that the distribution of vibrations during end milling into speed zones [15] allows determining, based on initial data during technological preparation, under what conditions machining will occur. Among the five speed zones, the third speed zone of vibrations is the most unfavorable for stable milling. It is the only one with high intensity AFO, while they are absent in other zones. However, it is precisely the third speed zone of vibrations that corresponds to milling of parts from hard-to-machine materials. Therefore, the search for an answer to the question of what influences the properties of the part during cutting is relevant, as the intensity of vibrations depends on them. It is known that the period of AFO during cutting is different from the period of free vibrations during idle motion [16]. It decreases. Thus, by connecting the part to the tool through cutting conditions, it is possible to influence its new properties through chip formation. Researchers focus on utilizing the damping properties of the feed [17]. Therefore, the task of determining how exactly the feed rate affects this becomes relevant.

2. EXPERIMENTS AND DISCUSSION OF RESULTS

For the investigation, a universal stand was utilized [15], which allows for the creation of various dynamic characteristics of the workpiece and recording the laws of its motion during milling on an oscillogram.

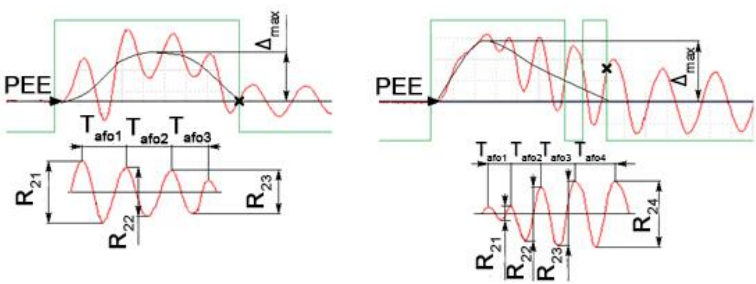
The investigation of the feed rate's influence on the dynamic characteristics of the workpiece was conducted during up and down-milling in the third speed zone with conditions that lead to the occurrence of high-intensity AFO. The initial data for the study are provided in Table 1.

Table 1- The initial data for conducting the research

The material of the workpiece being machined	Steel 3
The material of the milling cutter's cutting edge	Hard alloy
The stiffness of the elastic element of the part, j_{ee}, N/m	1746562
Free oscillation frequency of the elastic element of the part, f_{foee}, Hz	512
The stiffness of the milling cutter, f_{mc}, N/m	23986111
Free oscillation frequency of the milling cutter, f_{fomc}, Hz	1776
The diameter of the milling cutter, d_{mc}, mm	30
The number of teeth of the milling cutter, z	1
The helix angle of the milling cutter's tooth, ω, deg	0
Feed rate, S_z, mm/tooth	0.05; 0.1; 0.2; 0.3
The spindle rotation speed, n, rpm	355
The radial depth of cut, a_o, mm	0.3
The axial depth of cut, a_p, mm	4

The analysis of the workpiece motion during milling was conducted using fragments of oscillograms during cutting [15]. Based on these, dynamic characteristics such as the period T_{afo} and amplitude R_2 of accompanying free oscillation were determined. These were measured after straightening the oscillogram fragment using a Savitzky-Golay filter, as well as the maximum static deflection (Δ_{max}).

Figures 1-4 depict fragments of oscillograms during up and down-milling with various feed rates and checked parameters.



Up-milling Down-milling

PEE - position of elastic equilibrium; ► - tool entry point into the part; × - tool exit point from the part

Figure 1 - Fragments of the oscillogram of part vibrations during milling with a feed rate of S_z = 0.05 mm/tooth

Based on the measurement results of the part's vibration parameters during cutting, Tables 2-5 were constructed.

Table 2 - The parameters of the part's vibrations during milling with a feed rate of S_z = 0.05 mm/tooth

The parameters	The feed direction	
	Up-milling	Down-milling
T_{afo1}, 10^{-3} s	1.64	0.84
T_{afo2}, 10^{-3} s	1.76	1.12
T_{afo3}, 10^{-3} s	1.44	1.28
T_{afo4}, 10^{-3} s	-	1.48
f_{afo1}, Hz	609	1190
f_{afo2}, Hz	568	892
f_{afo3}, Hz	694	781
f_{afo4}, Hz	-	675
R_{21}, mm	0.086	0.019
R_{22}, mm	0.069	0.076
R_{23}, mm	0.061	0.092
R_{24}, mm	-	0.093
Δ_{max}, мм	0.065	0.094

The data in Table 2 indicate that the dynamic properties of the part during cutting are different from its properties before cutting. Moreover, they change throughout the cutting process with varying depth of cut. During up-milling, after plunging, the frequency of AFO is 16% higher than the natural frequency of the part. As the thickness of the layer to be cut increases, the AFO frequency increases by another 12% by the end of the cut. In down-milling, after after plunging with the maximum depth of cut, the frequency of AFO exceeds the natural frequency of the part by 57%. However, with the minimum depth of cut towards the end of cutting, the frequency of AFO decreases by 43%. Due to the differences in cutting in the shaping zone of the machined surface (at the beginning of cutting for up-milling and at the end of cutting for down-milling), the frequency of AFO during down-milling is 10% higher than during up-milling.

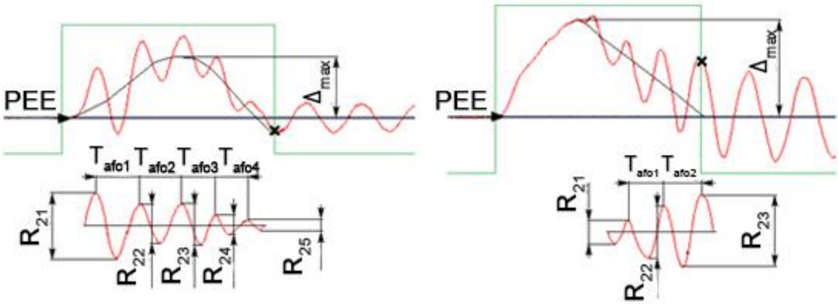
The amplitude of AFO decreases by 29% from the beginning to the end of cutting during up-milling, while during down-milling, it increases by 79% due to negative attenuation [18].

The maximum deflection of the part, which characterizes the action of the radial component of the cutting force, is 30% less during up-milling than during down-milling.

A characteristic feature of the feed rate's influence on the dynamic properties of the part during cutting is the dynamic stiffness index k_{dyn}, which indicates how much the dynamic stiffness differs from the static stiffness and is determined by the formula:

$$k_{dyn} = \frac{2\Delta_{max}}{R_2}.$$

During up-milling: $k_{dyn} = 1.51$.
During down-milling: $k_{dyn} = 2.02$.



Up-milling Down-milling

Figure 2 - Fragments of the oscillogram of part vibrations during milling with a feed rate of S_z = 0.1 mm/tooth

Table 3 - The parameters of the part's vibrations during milling with a feed rate of S_z = 0.1 mm/tooth

The parameters	The feed direction	
	Up-milling	Down-milling
T_{afo1}, 10^{-3}, s	1.72	1.24
T_{afo2}, 10^{-3}, s	1.52	1.44
T_{afo3}, 10^{-3}, s	1.24	-
T_{afo4}, 10^{-3}, s	1.24	-
f_{afo1}, Hz	581	806
f_{afo2}, Hz	657	694
f_{afo3}, Hz	806	-
f_{afo4}, Hz	806	-

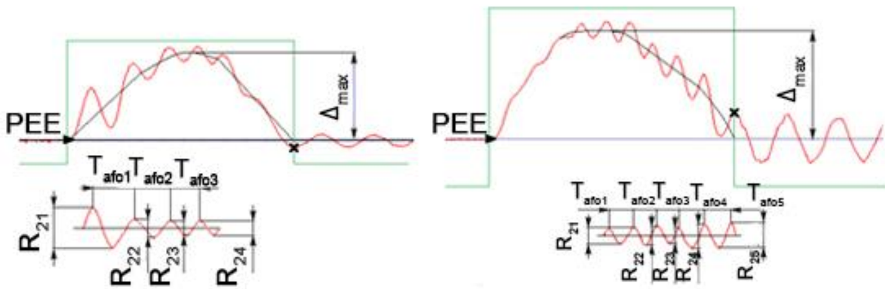
R_{21}, mm	0.088	0.032
R_{22}, mm	0.049	0.071
R_{23}, mm	0.054	0.099
R_{24}, mm	0.026	-
R_{25}, mm	0.012	-
Δ_{max}, мм	0.076	0.133

When up-milling with a feed rate of S_z = 0.1 mm/tooth, the frequency of AFO after plunging is 12% higher than the natural frequency of the part. By the end of cutting, it further increases by 28%. During down-milling with the same feed rate, the frequency of AFO after plunging is 36% higher than the natural frequency of the part. However, it decreases by 14% by the end of cutting. Moreover, the frequency of AFO in the shaping zone of the machined surface is 16% higher during down-milling than during up-milling.

The amplitude of AFO decreases by 86% from the beginning to the end of cutting during up-milling, while during down-milling, it increases by 68%.

The maximum deflection of the part during up-milling is 42% less than during down-milling.

The dynamic stiffness index during up-milling is k_{dyn} =1.73, while during down-milling, it is k_{dyn} = 2.69.



Up-milling Down-milling

Figure 3 - Fragments of the oscillogram of part vibrations during milling with a feed rate of S_z = 0.2 mm/tooth

When up-milling with a feed rate of S_z = 0.2 mm/tooth, the frequency of AFO after plunging is 20% higher than the natural frequency of the part. By the end of cutting, it further increases by 28%. During down-milling, the frequency of AFO after plunging is 55% higher than the natural frequency of the part. However, it decreases by 27% by the end of cutting. Moreover, the frequency of AFO in the formation zone of the machined surface is 23% higher during down-milling than during up-milling.

The amplitude of AFO decreases by 75% from the beginning to the end of cutting during up-milling, while during down-milling, it increases by 37%. It is worth noting that vibrations during cutting with an amplitude (R_2/2) up to 0.02 mm can be favorable for chip formation [19]. Such values were obtained during down-milling with a feed rate of S_z = 0.2 mm/tooth.

The maximum deflection of the part during up-milling is 20% less than during down-milling.

The dynamic stiffness index during up-milling is k_{dyn} = 4.35, while during down-milling, it is k_{dyn} = 8.91.

Table 4 - The parameters of the part's vibrations during milling with a feed rate of S_z = 0.2 mm/tooth

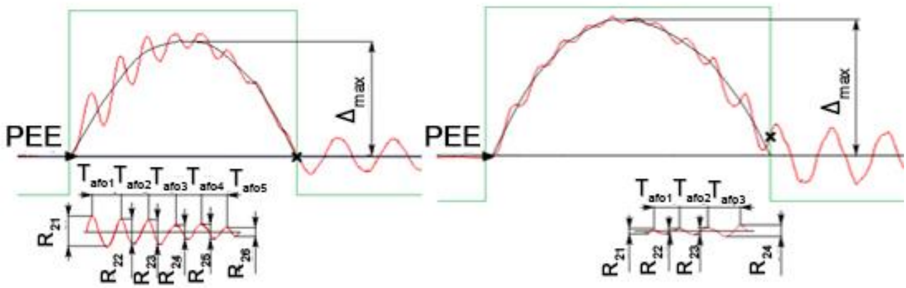
The parameters	The feed direction	
	Up-milling	Down-milling
T_{afo1}, 10^{-3}, s	1.56	0.88
T_{afo2}, 10^{-3}, s	1.40	0.88
T_{afo3}, 10^{-3}, s	1.12	0.96
T_{afo4}, 10^{-3}, s	-	1.04
T_{afo5}, 10^{-3}, s	-	1,2
f_{afo1}, Hz	641	1136
f_{afo2}, Hz	714	1136
f_{afo3}, Hz	892	1041
f_{afo4}, Hz	-	961
f_{afo5}, Hz	-	833
R_{21}, mm	0.057	0.022
R_{22}, mm	0.023	0.027
R_{23}, mm	0.020	0.020
R_{24}, mm	0.014	0.027
R_{25}, mm	-	0.035
Δ_{max}, мм	0.124	0.156

When up-milling with a feed rate of S_z = 0.2 mm/tooth, the frequency of AFO after plunging is 20% higher than the natural frequency of the part. By the end of cutting, it further increases by 28%. During down-milling, the frequency of AFO after plunging is 55% higher than the natural frequency of the part. However, it decreases by 27% by the end of cutting. Moreover, the frequency of AFO in the formation zone of the machined surface is 23% higher during down-milling than during up-milling.

The amplitude of AFO decreases by 75% from the beginning to the end of cutting during up-milling, while during down-milling, it increases by 37%. It is worth noting that vibrations during cutting with an amplitude ($R_2/2$) up to 0.02 mm can be favorable for chip formation [19]. Such values were obtained during down-milling with a feed rate of S_z = 0.2 mm/tooth.

The maximum deflection of the part during up-milling is 20% less than during down-milling.

The dynamic stiffness index during up-milling is k_{dyn} = 4.35, while during down-milling, it is k_{dyn} = 8.91.



Up-milling Down-milling

Figure 4 - Fragments of the oscillogram of part vibrations during milling with a feed rate of S_z = 0.3 mm/tooth

Table 5 - The parameters of the part's vibrations during milling with a feed rate of S_z = 0.3 mm/tooth

The parameters	The feed direction	
	Up-milling	Down-milling
T_{afo1}, 10^{-3}, s	1.04	0.88
T_{afo2}, 10^{-3}, s	0.96	0.92
T_{afo3}, 10^{-3}, s	0.96	1.12
T_{afo4}, 10^{-3}, s	0.92	-
T_{afo5}, 10^{-3}, s	0.92	-
f_{afo1}, Hz	961	1136
f_{afo2}, Hz	1041	1086
f_{afo3}, Hz	1041	892
f_{afo4}, Hz	1086	-
f_{afo5}, Hz	1086	-

R_{21}, mm R_{22}, mm R_{23}, mm R_{24}, mm R_{25}, mm R_{26}, mm	0.045 0.039 0.032 0.019 0.020 0.012	0.003 0.007 0.010 0.017 - -
Δ_{max}, мм	0.156	0.187

When up-milling with a feed rate of S_z = 0.3 mm/tooth, the frequency of AFO after plunging is 42% higher than the natural frequency of the part. By the end of cutting, it further increases by 11%. During down-milling, the frequency of AFO after plunging is 55% higher than the natural frequency of the part. However, it decreases by 21% by the end of cutting. Moreover, the frequency of AFO in the in the formation zone of the machined surface is 7% lower during down-milling than during up-milling.

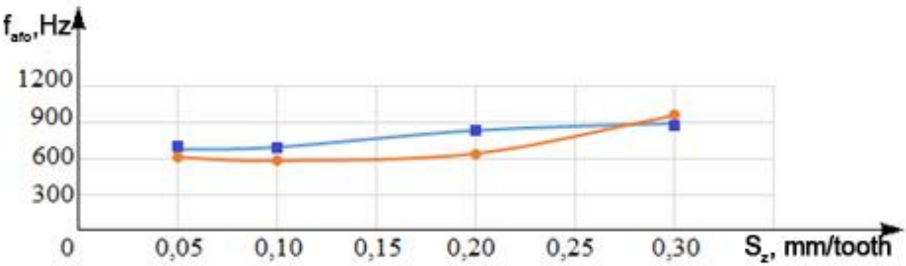
The amplitude of AFO decreases by 73% from the beginning to the end of cutting during up-milling, while during down-milling, it increases by 82%.

During conventional milling with a feed rate of S_z = 0.3 mm/tooth, the amplitude of AFO is less than 0.02 mm.

The maximum deflection of the part during up-milling is 16% less than during down-milling.

The dynamic stiffness index during climb milling is k_{dyn} = 6.93, while during conventional milling, it is k_{dyn} = 22.

The research results indicate that the feed rate S_z during up and down-milling affects the part's properties during cutting due to its influence with the thickness of the cut layer. For all feed rate values, the frequency of AFO is higher than the natural frequency of the part.



● – up-milling; ■ – down-milling

Figure 5 - Dependency of AFO frequency on feed rate

Correlation coefficient between AFO frequency and feed rate is 0.87 for up-milling and 0.98 for down-milling. These dependencies are described by the following regression equations:

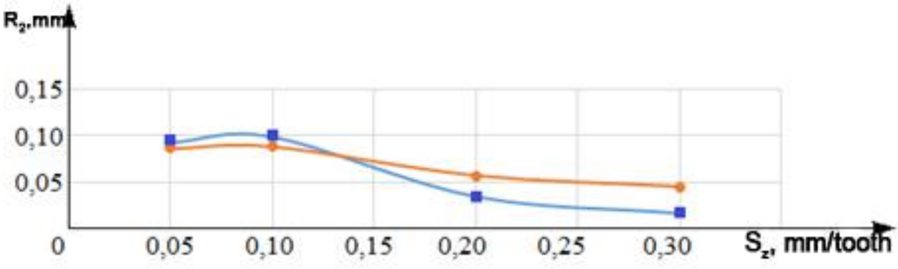
- for up-milling:

$$f_{afo} = 1392{,}5 \cdot S_z + 471{,}71. \quad (2)$$

- for down-milling:

$$f_{afo} = 937{,}63 \cdot S_z + 621{,}14. \quad (3)$$

Increasing the thickness of the cut layer, in addition to affecting the frequency of AFO, also influences the amplitude of AFO, which decreases in this case (Fig. 6).



● – up-milling; ■ – down-milling

Figure 6 – Dependency of AFO amplitude on feed rate

Correlation coefficient between AFO amplitude and feed rate is (-0.96) for up-milling and (-0.94) for down-milling. These dependencies are described by the following regression equations:

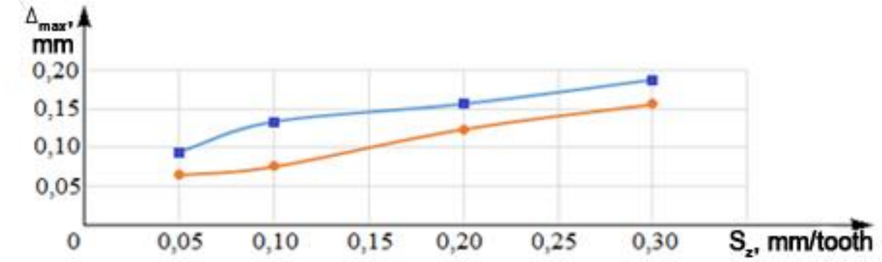
- for up-milling:

$$R_2 = -0{,}1858 \cdot S_z + 0{,}0992. \quad (3)$$

- for down-milling:

$$R_2 = -0{,}3525 \cdot S_z + 0{,}1183. \quad (4)$$

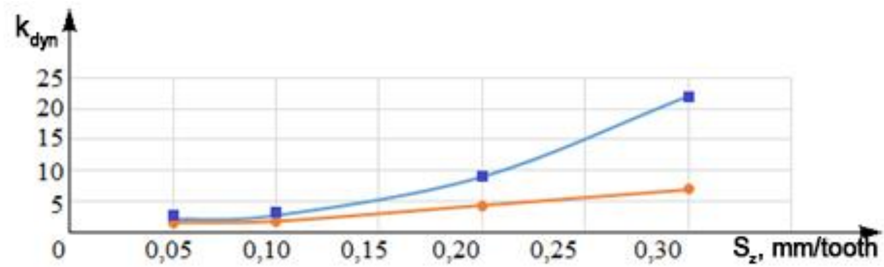
Increasing the thickness of the cut layer with increasing feed rate increases the static squeeze of the part during cutting Δ_{max}. Due to the differences in milling, it is larger in the down-milling than during up-milling (Fig. 7). This is influenced by the thickness of the layer at the beginning of cutting. It is greatest during down-milling and least during up-milling. Therefore, the radial component of the cutting force is more significant during down-milling. The squeeze of the part, with the same stiffness, will be greater in this case than during up-milling.



• - up-milling; ■ – down-milling

Figure 7 - Dependence of workpiece compression on feed rate

Furthermore, with an increase in feed rate, dynamic stiffness increases (Fig. 8). The correlation between them in up-milling is 0.98, and in down-milling it is 0.96. This influences the reduction of AFO intensity with an increase in feed rate.



• - up-milling; ■ – down-milling

Figure 8 - Dependence of dynamic stiffness on feed rate

The regression equation for face milling:

$$k_{dyn} = 40{,}201 \cdot S_z^2 + 8{,}5869 \cdot S_z + 0{,}8025. \quad (6)$$

The regression equation for peripheral milling:

$$k_{dyn} = 336{,}94 \cdot S_z^2 - 38{,}081 \cdot S_z + 3{,}0946. \quad (7)$$

3. CONCLUSIONS

The dynamic properties of the workpiece during cutting manifest themselves in the form of frequency and amplitude of accompanying free vibrations. As demonstrated by conducted research, the feed rate, as an element of cutting conditions, affects them.

The AFO frequency during cutting is higher than the natural frequency of the workpiece by (16-47)% in up-milling and by (36-55)% in down-milling. The variable layer being cut during end-milling affects the chatter frequency, which changes from tool engagement to exit by up to 28%. Due to the characteristics of up- and down-milling, the AFO frequency increases when using the former feed direction and decreases when using the latter.

The feed rate affects the dynamic stiffness of the workpiece during cutting, which increases with its increment. This influences the fact that with an increase in feed rate, the AFO frequency increases and its amplitude decreases. The dynamic stiffness is greater in down-milling than in up-milling.

The positive influence of the feed rate in reducing vibration intensity is beneficial for machining rigid workpieces. However, when milling thin-walled components, the radial cutting force component increases with feed rate increment. This negatively impacts machining accuracy due to the reduction in cutting depth caused by workpiece squeezing.

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ВПЛИВ ПОДАЧІ НА ДИНАМІЧНІ ВЛАСТИВОСТІ ТОНКОСТІННОЇ ДЕТАЛІ ПРИ КІНЦЕВОМУ ФРЕЗЕРУВАННІ

Анотація. *При призначенні режимів різання для кінцевого фрезерування тонкостінних деталей з важкооброблюваних матеріалів треба враховувати їх вплив на сталість обробки. Для цього треба знати, які види коливань діють і за яких умов вони виникають. Виконаними дослідженнями встановлено, що при різанні різні види коливань діють послідовно і тільки певний час. При кінцевому фрезеруванні через короткочасність різання виникають вимушені та супроводжуючі вільні коливання. Їх вплив на сталість процесу різання залежить від того, в якій швидкісній зоні коливань буде проходити фрезерування. Найбільш несприятливою є третя швидкісна зона коливань. Тільки в ній діють супроводжуючі вільні коливання великої інтенсивності. Швидкості різання для обробки деталей з важкооброблюваних матеріалів припадають саме на цю зону. На інтенсивність коливань впливають динамічні властивості деталі. При кінцевому фрезеруванні тонкостінних деталей вони характеризуються амплітудою та частотою супроводжуючих вільних коливань, які більше за частоту вільних коливань деталі. Тобто режими різання змінюють динамічні властивості деталі. Деякі дослідники зосереджуються на використанні демпфуючих властивостей подачі. Тому метою даної роботи було визначення того, яким чином подача впливає на динамічні властивості деталі при різанні. Для дослідження використовувався універсальний стенд, за допомогою якого можливо створювати різні динамічні характеристики зразка, який обробляється та записувати на осцилограмі закони його руху при фрезеруванні. Результати досліджень показали, що подача, як елемент режимів різання, впливає на динамічні властивості деталі при різанні. Вона створює змінний шар, який зрізається. Тому на протязі часу різання частота і амплітуда супроводжуючих вільних коливань при зустрічному і попутному фрезеруванні змінюються. Подача впливає на динамічну жорсткість. При збільшенні подачі динамічна жорсткість деталі збільшується. Це призводить до зменшення амплітуди супроводжуючих вільних коливань при фрезеруванні в третій швидкісній зоні коливань. Наведені у статті результати мають практичне значення для технологів у галузі авіаційного виробництва. Вони допомагають краще розуміти фізичні процеси, що відбуваються під час фрезерування, та розробляти оптимальні стратегії обробки тонкостінних деталей, до яких висуваються високі вимоги щодо точності розмірів та якості поверхні.*

Ключові слова: *фрезерування; фреза; тонкостінна деталь; подача на зуб; осцилограма; супроводжуючі вільні коливання.*