Studying the dynamics of cutting process by a face mill cutter

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Abstract. An overview of stepped end mills use for rough cutting of large allowances and finishing cut of flat surfaces is given, where they ensure a reduction in cutting forces, an increase in dynamic stability and performance rate. The study of oscillations in the direction of the longitudinal feed of the spindle and workpiece subsystems, as well as the spindle torsional subsystem, has been carried out by the simulation modeling method. Detailed pictures of the oscillations of these subsystems are obtained. Careful analysis of these oscillations using the basic principles of the regeneration theory of self-oscillations allows establishing their nature and mutual influence. It is established that the main reason for the increased dynamic stability of the stepped end mill as compared to the standard one is the reduction of the power load due to the group cutting scheme and an increase in the uniform distribution of the frequency spectrum of the cutting moment due to the variability of the actual angular pitch of the teeth. The revealed pattern serves as a methodological basis for the creation of progressive designs of stepped end mills. When developing them, it is necessary to look for new patterns of the relative position of the teeth when varying the difference in diameters of the stages and angular steps.

1. Introduction

The possibility of roughing flat surfaces on milling machines of medium size with standard face mill cutters is usually limited to a cutting depth of the order of 5 ... 6 mm, not only due to the lack of machine power, but mainly to the excitation of intense self-oscillations, drastically reducing tool life and equipment service life [1]. If it is necessary to remove a larger allowance in one transition, it is recommended to use stepped mills [2]. With a cut depth of 6 ... 14 mm, two-stage face mills are used, and at 12 ... 22 mm - three-stage [3]. The generator cutting scheme is implemented in standard face mills, and in the stepped – group ones that is wide thin chips are replaced by a few narrow but thicker ones. This is accompanied by a decrease in specific force and cutting temperature. Long-term experience of using these tools in domestic enterprises has shown that “stepped mills provide the ability to remove large allowances in a single transition without causing vibrations, increasing tool life by 2 times, reducing the time for detail processing to 50% and cutting power to 20–30%” [2]. The positive effect of the group cutting scheme in the form of reducing cutting force and increasing dynamic stability is also observed in end “corn” mill cutters with serrated end mills [4].

The stepped cutting scheme is also successfully used in mill cutters for finishing cut blade processing instead of grinding, using circular pan cutters [2] and composites inserts [5], providing high quality of machined surface, increased tool life and productivity. In addition to the traditional arrangement of the teeth, new installation schemes are offered in the steps with a uniform angular step: single and multi-row spiral-staged, shuttle, with uneven angular step and others [5].
To improve the performance of stepped end mills, it is important to optimize their design parameters (blade geometry, distribution of allowance between stages, selection of teeth arrangement and others) in order to reduce power and temperature loads of cutting inserts, their attachment points, tool cases; vibration level; conditions of formation and removal of chips [6-9]. At the same time, the question of the dynamic stability of the stepped mills has not been fully studied. The reasons for a sharp decrease in the level of self-oscillations compared to standard mill cutters during operation, which prevents the improvement of their structures, have not been established yet. The mere reduction of 20% of the power loads on the stepped mill due to lower cutting pressure on the blades is not possible to explain the significant increase in the dynamic stability of the tool. In this regard, the establishment of the dynamic behavior nature of the stepped end mills during operation is the actual task of modern engineering. The aim of the research presented in the article is to study the dynamic processes in the technological system of a milling machine using a stepped face mill.

2. Equipment and research technique

To find out the reasons for the increased dynamic stability of the operation of the stepped mill and quantitative degree of vibration suppression, the machining on a horizontal milling machine of mod. 6M82 planes of steel billet of 45 (HB=235) being standard due to TS 2-035-618-78 and two-stage face mill was compared. Both mill cutters have the same diameter of 160 mm, the number of carbide teeth - 10 and the geometry of the cutting blades: $\phi = 85^\circ$, $\phi_1 = 5^\circ$, $\gamma_{rad} = -11^\circ$, $\gamma_{os} = -10^\circ$. The radii of the teeth of a two-stage mill cutter are 80 and 70 mm, and their difference in height is 3 mm. In order to ensure the excitation of self-oscillations when working with a standard mill, the regime of rough symmetrical milling is adopted: $B = 120$ mm, $t = 6$ mm, $S_0 = 1.0$ mm/r (rotation), $v = 158…317$ m/min ($n = 315…630$ rpm).

The study of dynamics of the milling process was performed by the simulation modeling method [10]. The following machine coordinates were chosen: X – in the direction of the longitudinal table feed, Y – vertical direction, Z – in the direction of the spindle axis. The values of mathematical model parameters of the machine elastic system, determined experimentally, are given in Table 1, where they are indicated: $n$ – spindle rotation frequency, $f$ – natural oscillation frequency, $c$ – rigidity, $m$ – reduced mass, $I$ – inertia moment, $h$ – drag force coefficient. The nature and structure of oscillatory processes in the machine during cutting was established on the basis of the vibrational records and the vibration spectra analysis of the tool and workpiece subsystem contours and spindle torsion contour.

| TM Element | Coordinate or frequency, $n$, min$^{-1}$ | $f$, Hz | $C$, MN/m or N·m/rad | $m$, kg or kg·m$^2$ | $h$, N·s/m or N·s·m |
|------------|-----------------------------------------|--------|---------------------|--------------------|-------------------|
| Table      | X                                       | 94     | 44                  | 126                | 5742              |
|            | Y                                       | 97     | 132                 | 354                | 23598             |
|            | Z                                       | 479    | 787                 | 87                 | 22887             |
|            | X                                       | 185    | 304                 | 225                | 25752             |
| Sleds      | Y                                       | 110    | 519                 | 1083               | 78480             |
|            | Z                                       | 641    | 1556                | 96                 | 30597             |
|            | X                                       | 92     | 106                 | 321                | 17558             |
| Console    | Y                                       | 267    | 206                 | 73                 | 21719             |
|            | Z                                       | 105    | 1094                | 2507               | 147064            |
| Spindle with face mill | X                                    | 516    | 107                 | 10                 | 4651              |
|            | Y                                       | 431    | 175                 | 24                 | 10635             |
|            | Z                                       | 545    | 117                 | 10                 | 4577              |
| Main drive with face mill | 315                                  | 86     | 11959               | 0.04               | 3.41              |
|            | 400                                     | 73     | 9797                | 0.05               | 4.41              |
|            | 500                                     | 66     | 6618                | 0.04               | 3.87              |
|            | 630                                     | 63     | 4834                | 0.03               | 3.23              |
The conditions for the occurrence and suppression of self-oscillations were analyzed using the basic principles of their regeneration theory [10] that is taking into account the initial phase shift relative to vibration trace oscillations on the cutting surface.

3. Results and discussion

The magnitude of oscillation amplitude of TM contour when operating with two-stage (in the numerator) and standard (in the denominator) mill cutters at spindle rotation frequency \( n \) from 315 to 630 rpm and their correlations are obtained by modeling and presented in Table 2. A two-stage mill cutter instead of the standard one provides, at \( n = 315 \) and 630 rpm, a decrease by an order of magnitude and more range of oscillation of all TM contours. At \( n = 400 \) and 500 rpm the range of contour oscillations decreases less, namely, by 2 ... 3 times. The quality of the milling process dynamics is enhanced by reducing the magnitude of the cutting force moment and the change in its nature, as well as the conditions for regeneration of self-oscillations.

Table 2. Rating of the range of tm contour oscillations when working with two-stages and standard mill cutters

| \( n \) | \( S_{\text{min}} \) | \( \text{min} / \text{mm} \text{/min} \) | main drive \( \text{degrees} \) | \( \text{mm} / \text{min} \) | \( \mu \text{m} \) | ranges of contour oscillations | tool subsystems | workpiece subsystems |
|---|---|---|---|---|---|---|---|---|
| \( \text{min}^{1} \) | \( \text{mm/min} \) | \( \text{main drive} \) | \( \text{X} \) | \( \text{Y} \) | \( \text{Z} \) | \( \text{X} \) | \( \text{Y} \) | \( \text{Z} \) |
| 315 | 315 | 1.8/3.5 | 34/574 | 9/68 | 27/771 | 199/366 | 35/86 | 8/55 |
| \( = 0.51 \) | \( = 0.06 \) | \( = 0.13 \) | \( = 0.04 \) | \( = 0.54 \) | \( = 0.41 \) | \( = 0.15 \) |
| 400 | 400 | 11/0/19.8 | 202/463 | 43/82 | 149/347 | 683/2901 | 65/165 | 43/93 |
| \( = 0.56 \) | \( = 0.44 \) | \( = 0.52 \) | \( = 0.43 \) | \( = 0.24 \) | \( = 0.39 \) | \( = 0.46 \) |
| 500 | 500 | 18.0/27.6 | 280/685 | 69/161 | 255/736 | 624/2530 | 62/187 | 60/143 |
| \( = 0.65 \) | \( = 0.41 \) | \( = 0.43 \) | \( = 0.35 \) | \( = 0.25 \) | \( = 0.33 \) | \( = 0.42 \) |
| 630 | 630 | 0.3/32.0 | 23/575 | 6/128 | 21/575 | 159/1880 | 5/150 | 8/107 |
| \( = 0.01 \) | \( = 0.04 \) | \( = 0.05 \) | \( = 0.04 \) | \( = 0.08 \) | \( = 0.03 \) | \( = 0.07 \) |

To estimate the force effect of a two-stage mill cutter on TM in comparison with a standard mill cutter, in the course of simulation modeling, we calculated the change in time of \( M_{c} \) cutting force moment for both mill cutters. A preliminary simplified calculation [11] showed that, given the processing conditions adopted in the study, the circumferential cutting force should decrease by about 20% due to the replacement of the generator scheme for cutting the teeth with a group. The results of the simulation calculation of the cutting moment in the form of time graphs and frequency spectra obtained from them are presented in Figure 1. To eliminate the effect of intense vibrations accompanying the cutting process with a standard mill cutter with a cutting depth of \( t=6 \) mm, the time graph of the cutting force moment was built by increasing the corresponding graph by 6 times at \( t=1 \) mm. Under the same machining conditions, the cutting force moment by two-stage mill cutter is 290 H·m, and the standard one-stage – 340 H·m. Thus, its actual reduction was 15%. However, it cannot justify such a significant reduction in the level of TM oscillations.
Therefore, let us turn to the analysis of the frequency spectra of the cutting forces moments of both mill cutters (Fig. 1). Its schedule consists of regularly following pulses of the same shape in a standard mill cutter. The two-stage cutter graph has a different form and represents an alternation of pulses of different heights and widths. Changing the graph shape can be explained in the following way. The teeth of a single-stage standard mill cutter come into contact with the workpiece at regular intervals. These intervals are variable in a two-stage mill cutter, since the teeth of the second stage are located on a smaller radius than the radius of the teeth of the first stage, which leads to a delay in their entry into the workpiece. The delay time of the second stage teeth for the considered mill cutter with a symmetric milling of a 120 mm width workpiece is equivalent to a difference in the teeth pitch by 10.4 degrees. The delay is reflected in the character of the frequency spectrum of the cutting force moment of a two-stage mill cutter: the number of harmonics increases in it with a simultaneous decrease in their amplitudes. In other words, the force effect on TM becomes softer, which reduces the intensity of both forced vibrations and self-oscillations. The level of the latter, in addition, is affected by an increase in the distance between the teeth inside each stage, which leads to a change in the phase shift between the oscillations of the trace and current TM oscillations and, consequently, the conditions for self-oscillations regeneration.

Let us consider the conditions of their existence in bending subsystems of the tool and workpiece in the feed direction and the torsion contour of the main drive with the action of regeneration mechanism [10]. If the oscillating tooth of the mill cutter encounters a vibrating trace on cutting surface of the previous tooth with an initial shift of their phases in the range of 0...+180° that is one-half of self-oscillations wavelength is ahead, then oscillatory TM receives energy from the cutting process and self-oscillations are amplified. In case of their lagging in phase from the vibration trace in the range of 0...-180°, the energy from TM is pumped out and self-oscillations are suppressed. The maximum reinforcing

\[ M_c, H\cdot m \]

\[ A_M, H\cdot m \]

\[ f_r, Hz \]

\[ \text{Time, s} \]

\[ \phi, \text{Hz} \]

\[ a) \]

\[ b) \]

**Figure 1.** Graphs of time variation of the cutting moment \( M_c \) and its frequency spectra during quiet work with face mill cutters: a) – standard, b) – two-stage
or suppression effect of the regeneration mechanism appears when the values of the initial phase are +90° and -90°, respectively, corresponding to a quarter of the self-oscillation wavelength. If the initial phase shift is 0° or 180° (inphase or antiphase oscillations), then it has no effect on current oscillations.

TM also has the property of self-organization of its oscillatory movements in the cutting process. To minimize energy costs of their commission, it tends to adjust current oscillations to oscillations of the track on the cutting surface with a quarter of the wave ahead, regardless of the initial phase shift. Therefore, the trace effect is more pronounced than a smaller number of self-oscillation waves are fit on the cutting surface between adjacent mill cutter teeth, which is exactly the case in oscillations of the torsion contour of the considered TM.

Vibrational records of $X_c$ oscillations of the tool (1), workpiece (2) subsystems in feed direction and torsional vibrations $\varphi$ of the spindle (3) when operating with a two-stage mill cutter at different rotational frequencies: a – $n = 315$ rpm, b – $n = 400$ rpm, c – $n = 500$ rpm, d – $n = 630$ rpm

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Vibrational records of torsional spindle oscillations bending oscillations of the tool and workpiece subsystems in the direction of longitudinal feed from 315 to 630 rpm are presented in Figure 2. Figure 3 gives spectrographs of these oscillations. The graphs in Fig. 2a and 3a show that at a mill cutter rotation frequency of $n=315$ rpm in all TM contours, forced oscillations occur, main harmonics of which have a frequency equal to the frequency of the teeth entering the workpiece - 52 Hz. The teeth of the mill cutter first stage are separated from each other at a distance of 100.53 mm and move at a speed of 2.639 m/s. The wavelength of torsional oscillations at a frequency of 52 Hz is equal to 50.75 mm, that is, two waves of oscillations almost exactly fit between mill cutter teeth. The delay of the tooth mill cutter relative to
the track is close to zero. Therefore, the trace does not affect torsional oscillations of the spindle. The
range of the latter (1.8 degrees) in this case is only determined by oscillations in the magnitude of the
cutting moment and vibrational properties of the torsion contour. Is it possible to initiate self-oscillations
in the torsion contour at a proper frequency of 85.7 Hz? Their wavelength would be 30.79 mm. 3.27
self-oscillation waves could fit between adjacent teeth of the mill cutter, that is, current TM oscillations
would be 27% behind the track. This corresponds to almost best conditions for the suppression of
regenerative self-oscillations and therefore they are not excited.

Standard mill cutter work at \( n = 315 \) rpm is accompanied by bending spindle self-oscillations at a
frequency of 558 Hz. Taking into account a 20\% reduction in cutting force when operating with a two-
stage mill cutter, the expected frequency of bending self-oscillations of the spindle is 550 Hz. 20.95 self-oscillation waves having a length of 4.80 mm could fit between the adjacent teeth of this mill cutter. The 95% lag of current self-oscillations relative to the track determines almost zero regenerative activity of the secondary excitation. Therefore, the bending regenerative self-oscillations of the spindle are not excited. Under the action of a variable feed force, the tool subsystem performs bending forced resonant oscillations in the direction of the X axis with a range of 34 μm. Their spectrum represents a wide range of small amplitude harmonics whose frequencies are multiple to 26 Hz. The workpiece subsystem in the feed direction oscillates at the “toothed” mill cutter frequency with a range of 199 μm. In general, the level of TM oscillations is not high and the cutting process can be considered calm.

Oscillations whose main harmonics have a frequency of 64 Hz are established when a two-stage mill cutter with a rotational speed of 400 rpm is used in a torsion contour and X contours of the tool and workpiece subsystems (Fig. 2b and 3b). The torsional contour oscillates in the form of beats with a large range of 11.4 degrees (Fig. 4), creating a modulation of the cutting speed with a relative depth of 99%. The actual change frequency of 64 Hz cutting moment is slightly different from the “toothed” frequency of 66.7 Hz mill cutter due to the equivalent difference in tooth pitch, which has been mentioned above. At the same time, it is close to the proper oscillation frequency of a torsion contour of 72.7 Hz. Therefore, the oscillations of this contour are forced, almost resonant, which is explained by their large range and beat mode [13]. These oscillations can also be considered as a combination of forced and self-oscillations that occur in a non-autonomous self-excited system with a moderate detuning of excitation frequencies and its own [14]. The second approach also justifies the nature of these oscillations. The wavelength of torsional oscillations at the radius of the first stage teeth is 52.36 mm. Current TM oscillations are 92% behind track oscillations, and as a result, it gives them little support. At the proper frequency of 72.7 Hz torsion circuit, rotational regenerative self-oscillations cannot be excited, since 18% behind the tracks, which contributes to their suppression.

Torsional oscillations of the mill cutter cause additional changes in thickness of the layer being cut, proportional to the doubled sine of the twisted angle half [15]. With a torsional oscillations range of 11.4 degrees, an additional change in slice thickness is 57% of the nominal, which dramatically increases the cutting force oscillations. Therefore, intense forced oscillations are established in the bending subsystems of the tool and workpiece: in the first - resonant with a distributed spectrum, and in the second - almost harmonic. The amplitudes of forced oscillations of the tool and workpiece in the feed direction exceed the slice thickness. Therefore, the cutting process occurs with a periodic separation of the tool from the workpiece, as evidenced by intersection of 1 and 2 vibrational records in Fig. 2b. Although the relative modulation depth of the cutting speed is quite large (99%), it still cannot serve as an obstacle to the formation of bending self-oscillations of the tool subsystem at a frequency of 550 Hz, since its change frequency (64 Hz) is almost multiple to the frequency of entry into the teeth workpiece of one mill cutter stage (33 Hz). Bending spindle self-oscillations are not excited due to the track lag by
50%, which determines the absence of energy in TM to maintain them.

The mode of TM oscillations when operating at the next spindle speed of \( n = 500 \) rpm is close to the previous one (Fig. 2c and 3b), with the difference that self-oscillations in the torsion contour are not set as forced but on its proper frequency of 66 Hz with a range of 18. Their origin is determined by the regenerative effect due to the 58% lagging behind the track. Since the excitation effect of the track with such a lag is weak, full development of these self-oscillations requires a considerable time by standards of the oscillatory process (2.18 s). Figure 2c clearly shows the process of gradual increase in torsional self-oscillations and the increase in oscillations of the workpiece and tool caused by its increasing force effect. Harmonics are more pronounced in the oscillation spectrum of the latter compared to the previous case, whose frequency is close to the proper frequency of the system. (Fig. 3b and 3c). The frequency of the cutting speed modulation (66 Hz) in this case is about one and a half times more than the frequency of entry into the workpiece of teeth of one mill cutter stage (42 Hz). This prevents the occurrence of bending self-oscillations of the tool subsystem. Self-oscillations would not be excited even in the absence of the cutting speed modulation, since their lagging behind the track is 20%.

TM work at \( n = 630 \) rpm goes as calm as at \( n = 315 \) rpm, without detaching the tool from the workpiece (1 and 2 vibrational records are not intersected — Fig. 2d). Self-oscillations of the torsional contour at a proper frequency of 63 Hz cannot be excited, since even oscillations caused by random shocks at this frequency will be suppressed due to a 20% lagging behind the track. In this case, the group scheme of teeth cutting provides small differences in the magnitude of the cutting moment. Therefore, the forced torsional oscillations at a frequency of 104 Hz, close to the “toothed” one have a very small range — only 0.3 degrees. The regenerative effect does not also affect them due to the zero lag. Bending self-oscillations at a frequency of 550 Hz are not excited due to the lag behind the track by 48%. 23 μm resonant forced oscillations occur in the tool subsystem instead of self-oscillations, the main harmonic of which has a frequency of 52 Hz (Fig. 3d). Workpieces close to harmonic oscillations occur at the same frequency.

The use of simulation modeling made it possible to obtain a large amount of diverse information about the oscillations of main TM subsystems, which would be very difficult to implement in a full-scale experiment. Careful analysis of these oscillations using the provisions of the regeneration theory made it possible to establish their character and reveal mutual influence. In the general case, there are three possible structures of TM oscillatory processes in the process of face milling with a stepped tool:

- **Forced oscillations caused by the “toothed” frequency of the mill cutter are installed in all oscillatory contours of TM subsystems;**
- **Regenerative self-oscillations with corresponding proper frequencies of the contours, slightly increased due to cutting rigidity, are installed in one or several oscillatory contours of TM bending subsystems (these self-oscillations can also be caused by oscillatory properties of kinematic chain of the feed drive in the workpiece subsystem), and in the other contours of TM subsystems, forced oscillations occur at the “toothed” frequency of the mill cutter or proper torsional frequency of the spindle;**
- **Forced torsional or self-oscillations are installed in the drive of main movement, which are the source of forced oscillations in the oscillatory circuits of TM bending subsystems.**

The use of a stepped mill cutter instead of the standard one provides a significant reduction in oscillations in TM subsystems, the value of which varies from 2 to 15 times, depending on the combination of the machine oscillatory properties, constructional tool parameters and processing modes. The reason for increase in dynamic stability of the stepped mill cutter compared to the standard is the reduction of power load due to the group cutting scheme and the increase in uniform distribution of the frequency spectrum of the cutting moment due to variability of the actual angular pitch of teeth. The latter circumstance should be actively used in optimizing constructional parameters of stepped mill cutters by varying the mutual radial and angular position of teeth.

4. **Conclusion**

The study made it possible to reveal a detailed picture of oscillatory processes occurring in the main subsystems of the milling TM when operating with a stepped face mill cutter, and to establish the reasons
for its increased dynamic stability. This serves as a methodological basis for the creation of progressive designs of stepped end mills. When developing them, it is necessary to look for new schemes of the mutual position of teeth when varying the difference in diameters of the stages and angular steps.

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