



Article

Development and Geometric Optimization of High-Performance Face Mills for Chatter Suppression

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Abstract

In low-rigidity technological systems, face milling can cause undesirable vibrations, including forced and self-excited vibrations. These vibrations can be suppressed by selecting a mill with a variable tooth pitch. This paper analyzes existing face mill designs that implement this approach and describes the design of a developed mill with an adjustable tooth pitch. Experimental substantiation of the mill's performance demonstrated that proper selection of the difference between adjacent tooth pitches reduces the fundamental harmonics of self-excited vibrations by a factor of 28.

Keywords: face mill; forced vibrations; self-excited vibrations; variable tooth pitch; vibration suppression

1. Introduction

One of the key indicators of machining reliability is the absence of, or minimal, vibration in the technological system (TS). Vibrations degrade the precision and quality of a machined surface, as well as the service life of tools and equipment, and machining productivity, and negatively affect working conditions. Therefore, eliminating vibrations is a pressing issue in mechanical engineering.

In face milling with a low-rigidity TS, which is caused by the machine's tool design, workpiece geometry, or increased tool overhang from the spindle, two types of vibration can occur: forced or self-excited vibrations. For forced vibrations, the main concern is to avoid resonance, i.e., their frequency must not coincide with the natural frequencies of the system's components. However, self-excited vibrations are considered the most dangerous and difficult to suppress. In practice, mitigating them often requires reducing cutting parameters or the number of tool teeth, which, in turn, leads to a loss of productivity. Numerous and diverse methods for suppressing self-excited vibrations in milling developed to date are classified into passive, active, and those based on the destruction of the regenerative effect [1]. The advantage of the latter is the prevention rather than the

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attenuation of occurring vibrations. The authors chose this approach for combating vibrations since it is quite simple and does not require the use of complex and expensive equipment, unlike the first two.

Suppression of self-excited vibrations without loss of productivity is possible by creating a targeted influence on their regeneration mechanism [2]. During cutting processes, regardless of the initial conditions, ongoing self-excited vibrations spontaneously tune themselves to the wavy surface left by the previous pass, with a phase lead of half a wavelength. In each cycle, the uncut chip thickness is greater when the tool tooth exits the workpiece than when it enters. This causes the radial cutting-force component in the second half of the oscillatory cycle to exceed that in the first half, thereby supplying energy to the TS that sustains and intensifies the vibrations.

A targeted countermeasure consists of forcibly shifting the phase of the self-excited vibrations to the opposite; that is, making them lag behind the wavy surface by half a wavelength. In this case, energy is no longer pumped into the oscillating TS but is extracted from the system during each cycle due to the reversal of the chip thickness pattern—the maximum chip thickness now occurs at entry.

This targeted intervention can be implemented either by varying the tooth pitch or by modulating the cutting speed [3]. The first method is applicable only to multi-tooth tools, whereas the second is universal but more complex, as it requires generating a periodically varying spindle speed, which is limited by spindle inertia. This paper does not aim to analyze the second method. For vibration suppression using the first method, the wavy surfaces left by adjacent teeth must be in antiphase [4]. This condition is achieved when the difference between their pitches equals half the wavelength of the surface undulation.

Variable tooth pitches for improving the dynamic stability of milling were proposed by Hahn R.S. [5] in 1952. Later, the theoretical substantiation of this approach was carried out by Slavicek J. [6], Opitz H. [7], Vanherck P. [8], Kedrov S. [4], Tlustý J. [9], Budak E. [10], Zhang Z. [11], Özşahin [12], Ba S. [13], Nie W. [14,15], Xiao Y. [16], Trivikrama Raju C. [17], and Pehlivan [18], among others.

Budak E. [10] developed an analytical method for designing mills with non-constant pitches to improve dynamic stability. This method demonstrated good results and made it possible to expand the stability boundaries. The limitation of this method is that it was developed for end mills. Iglesias A. et al. [19] presented a method for selecting a tooth pitch for face milling operations, using an iterative numerical approach based on semi-discretization. This method increased the material removal rate threefold compared to standard mill designs, but its effectiveness is limited to specific machining conditions. The authors of [20] used a method for calculating the required phase shift between adjacent teeth. They managed to increase the depth of cut by 126 percent, while reducing cutting forces by 53 percent. In [21], the authors applied topological optimization combined with laser powder bed fusion. This technology made it possible to achieve the required dynamic characteristics of the mill body for specific technological conditions. A significant drawback of this method is the high costs of the equipment used. The authors of [22] proposed a method for rapid calculations of stability boundaries for variable-pitch mills. They managed to increase the calculation speed significantly. In [23], the authors proposed a method for analyzing the dynamic stability of end mills using a non-iterative multi-frequency approach with the Nyquist criterion to check stability.

Most reviewed works on suppressing regenerative self-excited vibrations apply only to end mills. For face mills, such studies are few. Moreover, none of the existing scientific works propose a face mill design that would allow for adjusting the tooth pitch without replacing the body. World-renowned cutting tool manufacturers, including Sandvik Coromant [24], produce face mills only with a fixed pitch: coarse, medium, fine, or alternating.

Since the middle of the last century, variable-pitch mills have been used in mechanical engineering to improve machining dynamics [25]. However, a variable tooth pitch suppresses self-excited vibrations only at one specific cutting speed [4]. Thus, the scientific problem addressed in this work is the absence of a design solution that would provide:

- The ability to adjust the tooth pitch of a face mill without replacing the body;
- High locating accuracy of cutting inserts when using standard indexable inserts;
- Versatility of application for various cutting conditions.

The aim of this study is the development, manufacturing, and experimental substantiation of a face mill design with an adjustable variable tooth pitch, ensuring effective vibration suppression during milling by readjusting the tooth pitch without replacing the body, and a quantitative assessment of the effectiveness of self-excited vibration suppression compared to a uniform-pitch mill.

The scientific contributions of this study are as follows:

1. Theoretical contribution: The authors have developed and experimentally confirmed a new principle for creating an adjustable variable tooth pitch of a multi-tooth tool, based on securing the teeth with a wedge in a common annular groove of the body. In contrast to known analogs, the proposed solution ensures arbitrary changes in the angular position and number of teeth without replacing the body. For the first time, the possibility of practical implementation of the analytical phase-shift model for face mills with an adjustable pitch has been experimentally confirmed, achieving a 28.3-fold reduction in the first harmonic of self-excited vibrations.
2. Experimental contribution: New quantitative data on the dynamic behavior of variable-pitch face mills in low-rigidity technological systems have been obtained, including spectral analyses of cutting forces for the first and second harmonics of self-excited vibrations. It has been shown that shifting the even-numbered teeth by a quarter of the wavelength provides suppression of the first harmonic by 28.3 times (from 466.3 N to 16.5 N).
3. Practical contribution: The proposed design reduces tooling costs by 40–60% compared to using several fixed-pitch mills for different machining conditions and provides an increase in tool life of more than 25% due to reduced dynamic loads. Furthermore, the developed principle can be extended to other types of multi-tooth tools.

This work presents an original design of a face mill with an adjustable variable pitch, ensuring effective vibration suppression during cutting by readjusting the tooth pitch without replacing the body. A common annular groove on the tool body is used for locating the cutting inserts, which eliminates the need for high-precision machining of insert pockets and ensures minimal radial runout of the teeth.

Analysis of Previous Designs of Face Mills

To find useful design ideas for the mill, a patent search was conducted using Russian sources classified under index B23C 5/06. One of the earliest technical solutions for adjusting the pitch and number of teeth of face mills is described in USSR Inventor's Certificate [26]. The solid tool body features an annular groove for the teeth, with trapezoidal clamping wedges located between them (Figure 1). Diametrical slots, offset from each other in the axial direction of the mill, are made in the body; these slots accommodate screws that are threaded into the wedges to secure the teeth in the body. The number of teeth and the variable pitch between them are changed by replacing the clamping wedges. The drawbacks of this design are the inability to smoothly vary the tooth pitch and the need to manufacture a new set of wedges for each mill configuration.

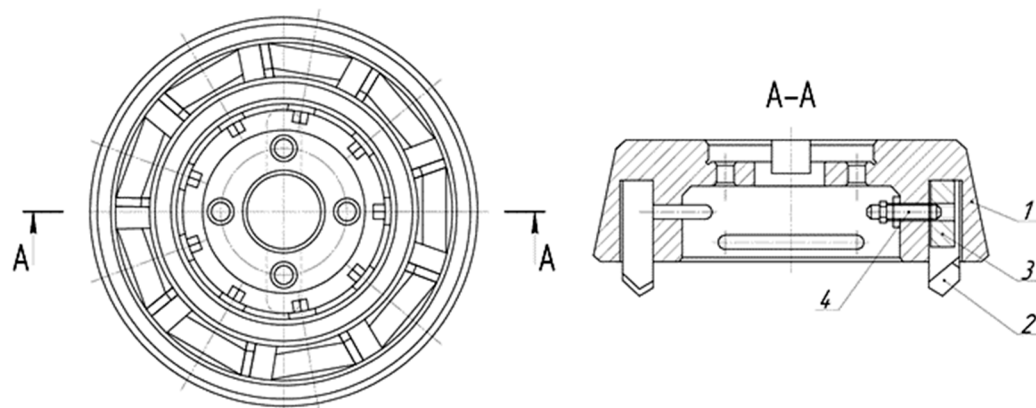


Figure 1. A face mill described in USSR Inventor's Certificate No. 390876: 1—body; 2—tooth; 3—wedge; 4—screw. Adapted from [26].

Another design of a modular face mill [27] consists of two coaxially mounted bodies: an outer ring carrying the odd-numbered roughing teeth, and an inner hub inserted into it, carrying the even-numbered finishing teeth (Figure 2). The angular pitches between the odd and even teeth are adjusted by rotating the two bodies relative to each other. All mill teeth are equipped with identical indexable inserts, which are clamped by holders using screws against angular chamfers on the mill bodies. Specifically, the odd-numbered inserts are clamped against the angular chamfer on the outer ring, while the even-numbered inserts are clamped against the angular chamfer on the hub. The design can smoothly adjust the alternating variable tooth pitch. However, it does not allow the number of teeth to be changed. Another drawback is the low locating accuracy of the inserts. With the clamping method, the insert is constrained in five degrees of freedom instead of six: three are constrained by the support surface of the holder, and two by the thrust surface of the angular chamfer. The remaining one rotational degree of freedom allows a slight rotation of the insert's cutting corner relative to the pin on the holder, which, in turn, leads to variations in the undeformed chip thickness, accelerated wear of that insert, increased tooth runout, and reduced workpiece surface quality.

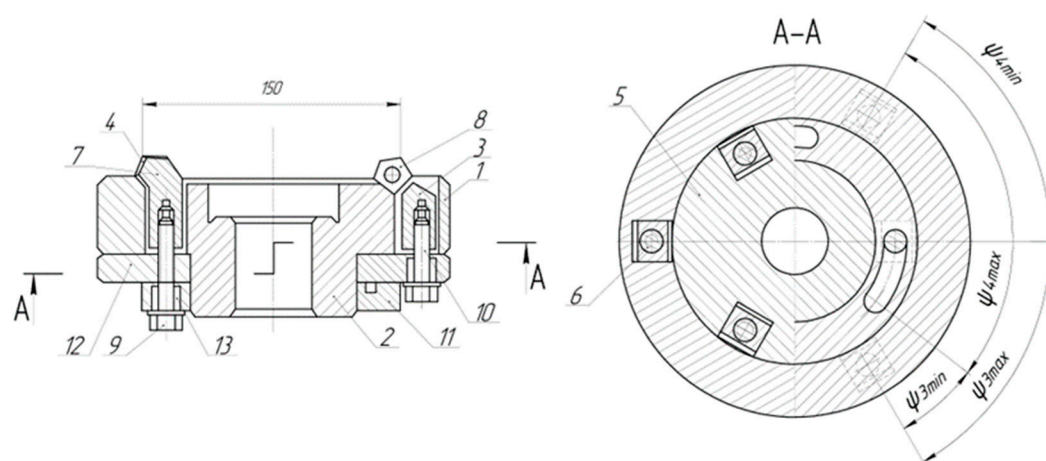


Figure 2. A face mill described in USSR Inventor's Certificate No 814597: 1, 2—body; 3—roughing teeth; 4—finishing teeth; 5—touching surface; 6—groove; 7—holder; 8—cutting plate; 9, 10—screw; 11, 12—support ring; 13—annular groove. Adapted from [27].

The next design of a special face mill was used to experimentally evaluate the effectiveness of suppressing self-excited vibrations using a variable tooth pitch [28]. On the periphery of a solid cylindrical tool body, two annular T-shaped grooves were made. Left-

hand turning tools, serving as the mill teeth, were secured in these grooves using bolts (Figure 3). The design is capable of changing the number of teeth and adjusting their variable pitch. Its drawbacks include the complexity and high labor intensity required to precisely adjust the variable pitch while ensuring minimal tooth runout. Furthermore, this design does not employ indexable inserts.

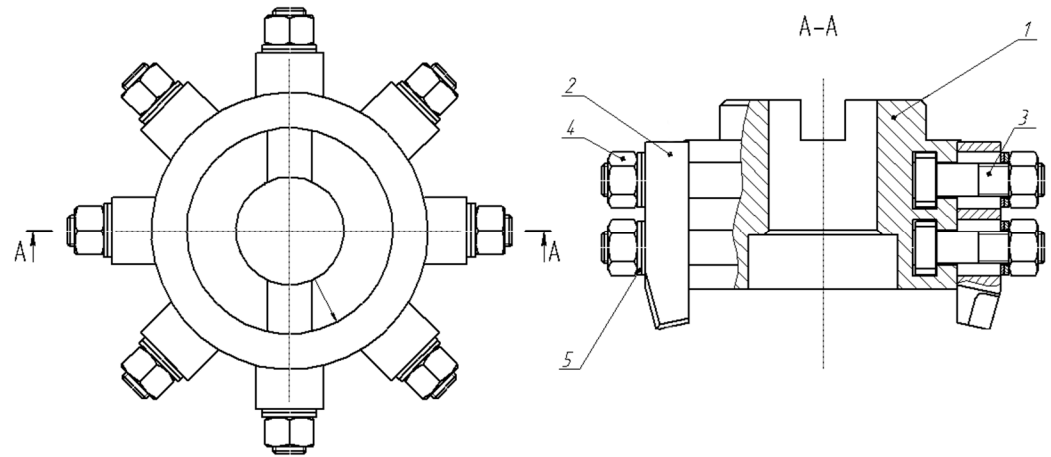


Figure 3. Adjustable pitch face mill: 1—body; 2—tooth; 3—pin; 4—screw; 5—puck. Adapted from [28].

The design, according to USSR Inventor's Certificate No. 1445871 [29], was adopted as a prototype for our mill. On the front face of the assembled tool body, an annular groove is made in which evenly spaced teeth are placed (Figure 4). These teeth carry mechanically clamped round indexable inserts with an offset toroidal rake surface, as well as wedge clamps that secure the teeth in the groove by wedging when tightened against the body with screws. The design can change the number of tool teeth and arbitrarily adjust their pitch by rotating the conical cutting plate with an offset toroidal rake surface about its axis. A drawback of the design is the need for precise machining of the pockets in the holders to ensure an acceptable runout of the cutting inserts relative to the tool body. Another disadvantage is the limited range of tooth pitch variation.

In addition to self-oscillations, the variable tooth pitch can also damp forced oscillations. To eliminate these, pitch unevenness is established from the following condition [4]:

$$\varepsilon = (t_{\max} - t_{\min})/t_{\text{av}} = n z / 60 f, \quad (1)$$

where t_{av} , $t_{\max}$, and $t_{\min}$ are the average, maximum, and minimum step sizes of the mill; z is the number of mill teeth; n is the mill rotation speed, rpm; and f is the oscillation frequency, for the suppression of which the step difference and their unevenness are calculated, Hz.

Using this condition, it is possible to determine the required step unevenness to suppress the first harmonic of forced oscillations excited by the uniform placement of teeth. The frequency of teeth passing is $f = n z / 60$. Substituting its value into Formula (1), we obtain $\varepsilon = 1$. It follows that $t_{\max} - t_{\min} = t_{\text{av}}$. Let us find the values of $t_{\max}$ and $t_{\min}$ for an even number of teeth by expressing the length of the cutting surface L as the sum of the tooth pitches:

$$L = 0.5 z t_{\min} + 0.5 z t_{\max} = 0.5 z t_{\min} + 0.5 z t_{\min} + 0.5 t_{\text{av}} = z t_{\min} + 0.5 L / z = z t_{\min} + 0.5 L, \quad (2)$$

then,

$$t_{\min} = L / 2 z; \quad t_{\text{av}} = L / z; \quad t_{\max} = L / 2 z + L / z = 3 L / 2 z, \quad (3)$$

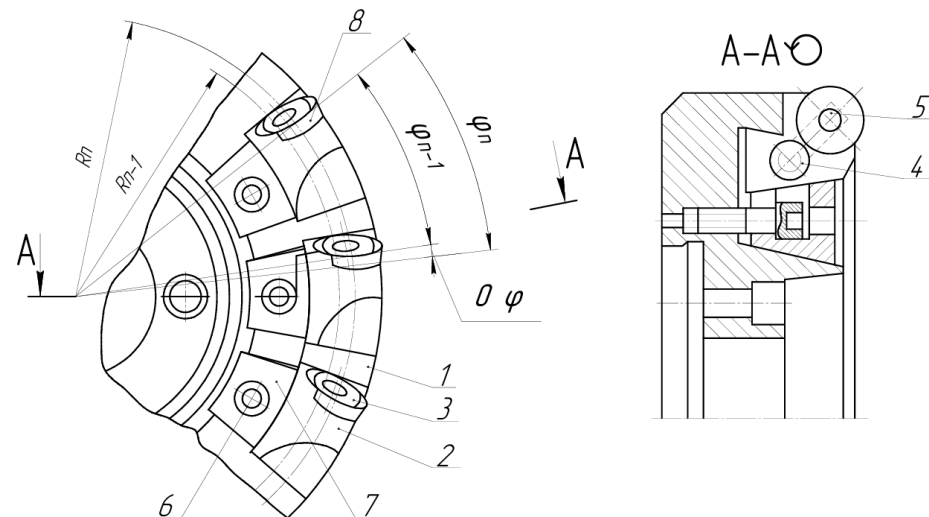


Figure 4. A face mill described in USSR Inventor's Certificate No. 1445871: 1—body; 2—holder; 3—chisel; 4—screw; 5—pin; 6—screw; 7—clamp; 8—cutting plate. Adapted from [29].

Another method for eliminating forced vibrations is described in Russian Patent No. 2710816 [30]. To prevent resonance in the TS, the teeth in the mill are installed with non-repeating pitches arranged in an ascending–descending sequence. The patent presents formulas for determining the non-repeating angular pitches of teeth for even and odd numbers of teeth, as well as examples of calculated angular pitch sets for eight and nine teeth.

The machine-building industry uses standard face mills with mechanically clamped indexable inserts arranged at a constant pitch (Figure 5) [31]. In such mills, pentagonal and round negative inserts are mounted on pins at the centers of inclined support surfaces on holders installed in grooves on the periphery of the tool body, parallel to its axis. The holders can be moved within their grooves using screws threaded into their ends. When moved until they stop, the holders secure the inserts by pressing their lateral faces against angular chamfers formed at the intersection of the holder grooves with an annular groove on the front face of the mill. This technical solution secures the inserts with a movable holder while simultaneously locating them against a common annular groove. The solution simplifies and reduces the cost of tool manufacturing by replacing the complex, labor-intensive process of milling individual insert pockets. It is well-suited for use in the design of the mill under development.



Figure 5. Face mill in accordance with GOST 26595-85. Adapted from [31].

2. Materials and Methods

The face mill was designed, manufactured, and tested at the Department of Technology and Equipment of Mechanical Engineering Productions, Irkutsk National Research Technical University (Figure 6). The mill teeth (holders with inserts) were made of Steel 45 (analog of 1045), the indexable inserts were made of carbide grade OC2125, and the screws securing the inserts were made of 40Cr steel. Milling experiments were carried out on a DMU80P Duo Block (DMG, Pfronten, Germany) machining center with a vertical spindle orientation and no coolant, using Steel 35 workpieces with a width $B = 134$ mm.



Figure 6. Cutting scheme: 1—cutting tool; 2—workpiece; 3—Kistler 9253B23 dynamometer.

The refusal to use cutting fluid was due to the need to ensure identical cutting conditions for a correct comparative analysis of the vibration components, since the use of coolant introduces additional variables that could distort the results of dynamic force measurements.

Cutting-force components were measured with a Kistler 9253B23 dynamometer (Kistler Group, Winterthur, Switzerland). This dynamometer provides high-quality recording of cutting-force values and is therefore widely used in research [32]. The test was repeated eight times.

Steels 35 and 45 (analogues of 1035 and 1045, respectively) were chosen for the experiments since they are the most common structural materials in general mechanical engineering and form the basis of the nomenclature of parts that are machined with face mills [33,34]. Their use as standard samples ensures the representativeness of the results and comparability with data from other studies in the field of cutting dynamics.

In general terms, the research methodology consisted of five stages: 1—analysis of existing face mill designs and identification of their limitations; 2—development of a new face mill design with an adjustable pitch based on the formulated requirements; 3—manufacturing of a prototype face mill with an adjustable tooth pitch; 4—experimental verification; 5—data analysis and evaluation of the effectiveness of self-excited vibration suppression. This sequence is shown in the flowchart in Figure 7.

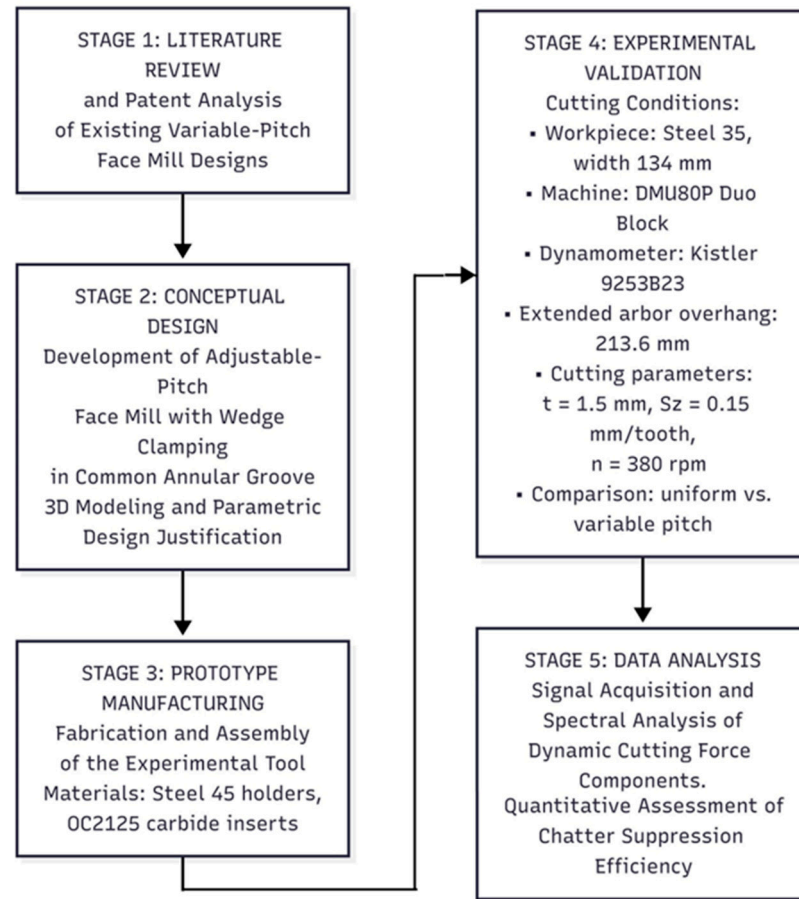


Figure 7. Flowchart of the research methodology illustrating the five consecutive stages.

3. Results

3.1. An Analysis of Face Mill Designs Allows for the Following Conclusions

1. There are two practical options for implementing variable tooth pitch. In the first design option, the tool needs to have two coaxial bodies, one of which carries odd-numbered teeth, and the other even-numbered teeth. The mutual rotation of the bodies ensures an alternating variable pitch. In the second design option, the tool body needs to have an annular groove at the end or periphery where the teeth are positioned and secured by friction; for example, when using wedge clamps. This second option offers broader technological capabilities for the tool, allowing for the creation of different pitch variations, such as alternating or ascending–descending pitches.
2. The second design option allows different numbers of teeth with arbitrary pitches to be mounted on a single tool body. When working on low-power, low-rigidity machine tools or machining flexible workpieces, mills with the fewest possible teeth help reduce vibrations. Conversely, powerful, rigid machine tools can operate with the maximum feasible number of teeth, thereby increasing productivity.
3. To simplify the design, it is advisable to locate the indexable inserts on the repositionable teeth using a common annular groove on the tool body.

3.2. Face Mill Design

Based on the known technical solutions, we developed a face mill design that can prevent either self-excited or forced vibrations of the TS during operation, depending on its adjustment (Figure 8).

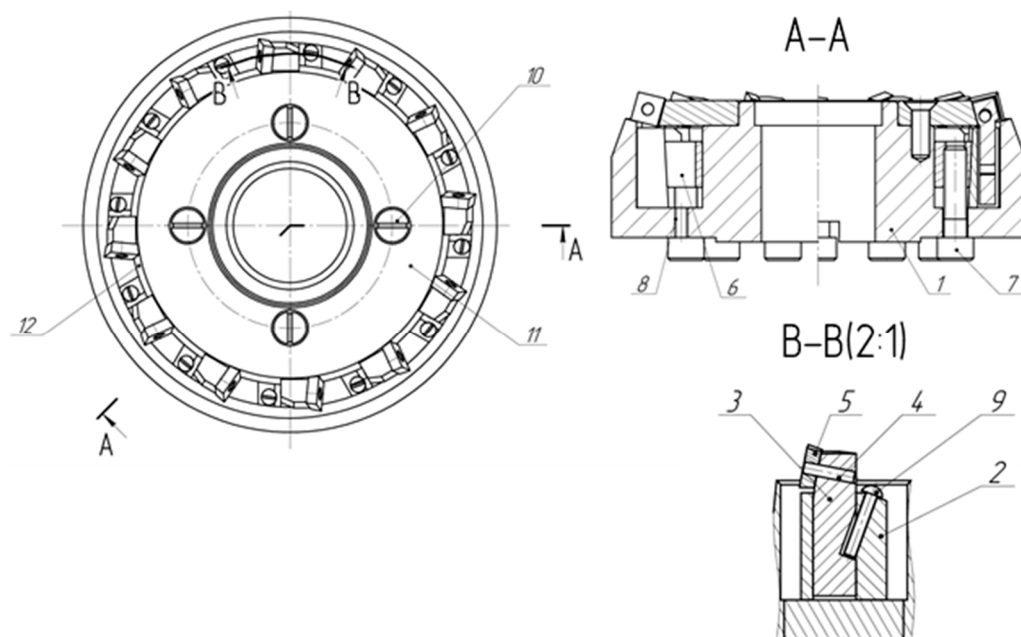


Figure 8. A vibration-free face mill design: 1—body; 2—support; 3—holder; 4—screw; 5—cutting plate; 6—wedge; 7—screw; 8—threaded hole; 9, 10—screw; 11—disk; 12—Base surface.

A coaxial annular groove was made on the front face of the monolithic cylindrical body (1). Supports (2) were placed in this groove at a specified pitch and secured in the required angular position by an annular wedge clamp (6) when screws (7)—which pass freely through holes in the bottom of the body (1)—are tightened into the clamp.

Locking of supports (2) by the wedge clamp (6) occurs due to self-locking of their contacting surfaces, which are inclined at 3° to the tool axis (a smaller angle than the friction angle of the steel components). Between the holes for screws (7) in the bottom of the body (1), there are additional threaded holes (8), into which screws (7) can be inserted to push the clamp (6) away, thereby releasing the supports (2).

Supports (2) have longitudinal grooves into which holders (3) are inserted. The heads of these holders feature inclined support surfaces for positive indexable inserts with a clearance angle of 7° . At the center of the support surfaces, pins (4) are pressed in to mount inserts with a central hole. In the side walls of the support (2), inclined threaded holes are provided, into which screws (9) are threaded; these screws bear against the chamfers on the side surfaces of the holders (3). On the front face of the body (1), a precisely machined land is provided, whose outer cylindrical surface is coaxial with the mill's mounting bore of a 50 mm diameter. A disk (11) with a conical side surface (12) is fitted onto this land and secured by screws (10). The tips of the square inserts installed in the mill lie on a circle of 160 mm diameter, providing a tool entry angle of 75° and a tool exit angle of 15° . Each insert is located and clamped by tightening the screw (9), which causes the holder to move along the groove in the support (2) and, via the pin (4), presses the insert (5) with its lateral faces against the common groove formed by the conical side surface of the disk (11) and a narrow conical surface on the front face of the body (1). The cutting force generated during machining further tightens the clamping of the insert.

3.3. Mill Adjustment

The mill adjustment is performed using a Zoller Genius 3 measuring machine, an ODG-2 optical measuring head, or similar equipment to measure the tool tooth pitches. Before adjustment, loosen the screws (9) and supports (2) by unscrewing the screws (7). Then, release the wedge clamp (6) after screwing them into the threaded holes (8). Then,

the screws (7) should be returned to their original positions, and the desired angular position of the support (2) is adjusted by sliding it along the annular groove. Finally, the screws (7 and 9) are tightened.

3.4. Design Parameters Justification

The primary parameter is the diameter at which its teeth are located. A diameter of 160 mm was chosen because it is one of the most commonly used diameters for medium-sized milling machines. The number of teeth was chosen to be 12, given the possible placement within the mill and the pitch adjustment.

During operation, a cutting force acts on the mill tooth, causing it to shift within the housing's angular groove. To prevent shifting, a frictional force greater than the cutting force is created in the groove by tightening the wedge clamp (6) and the screws (7) with a torque wrench. To evenly distribute the tightening force, twelve narrow radial grooves are cut into the annular clamp (6), dividing it into equal sectors that are connected into a monolith by thin bridges along the inner diameter. Let us determine the diameter of the screw (7), made of 40X steel, based on the tensile strength [35], and provided that each tooth is secured by one sector of the clamp (6). The following limiting cutting mode was selected for a steel 45 workpiece: cutting width $B = 130$ mm, cutting depth $t = 8$ mm, feed per tooth $S_z = 0.2$ mm/tooth, and spindle speed $n = 400$ rpm. The calculated [36] tangential component of the cutting force P_z is 1727 N. To balance it with wedge clamping of the tooth, the screw (7) should create an axial force $R_{ax} = 4361$ N [21]. From the tensile strength condition [37,38], the minimum internal diameter of the screw thread d_1 is 6 mm, which corresponds to the M8 screw. To enhance fastening reliability, an M10 screw was used.

Locating the indexable inserts in the repositionable teeth in the radial and axial directions of the tool is accomplished using their lateral faces against a common annular groove on the mill face. With such mounting, positive inserts acquire a doubled clearance angle. When machining structural steels and gray cast irons with carbide mills, the clearance angles of the main cutting edges, which provide an optimal tool life, range from 12° to 15° [22]. To achieve these values in our tool design, the milling inserts should have a clearance angle of 7° . However, such inserts could not be found among standard milling inserts.

Therefore, turning inserts SCMT 120408, which have a central hole and a clearance angle of 7° , were used. Contact between the lateral faces of the inserts and the groove is ensured by the holder support surface's inclination. During three-dimensional modeling of the design, the required inclination of the holder support surface was determined to be $10^\circ 48' +15'$ in the longitudinal direction and $2^\circ 44' +15'$ in the transverse direction. To protect the cutting edges from chipping, the lateral faces of the inserts contact the groove with their lower non-working edge, providing an angular clearance of $1^\circ +15'$.

3.5. Testing the Mill in Operation

A face mill of 160 mm diameter with 12 teeth and an entering angle of 75° was adjusted to both uniform and non-uniform tooth spacing. Milling was performed at a depth of cut $t = 1.5$ mm, feed per tooth $S_z = 0.15$ mm/tooth, and spindle speed $n = 380$ rpm. The cutting speed was selected in accordance with the recommendations of the carbide cutting insert manufacturer (JSC "KZTS").

The depths of the cut and feed per tooth were chosen based on the results of preliminary experiments, the purpose of which was to limit the vibration level in the low-rigidity TSs to values ensuring measurability and repeatability of the data.

To provoke self-excited vibrations by reducing the rigidity of the TS, the mill was mounted on an extended arbor with an overhang of 213.6 mm from the spindle face. For comparison, the standard arbor gives an overhang of 138.5 mm.

The mill with a constant tooth pitch operates with the excitation of self-excited vibrations, accompanied by characteristic noise (Figure 9a). Spectral analysis of the feed force vibration signal (Figure 9b) showed that the first harmonic of the self-excited vibrations has a dynamic amplitude of 466.3 N at a frequency of 245.3 Hz, while the second harmonic has an amplitude of 212.7 N at 495.6 Hz. In addition, the spectrum clearly shows peaks of the spindle rotation frequency (6.3 Hz) and the tooth passing frequency (70.1 Hz).

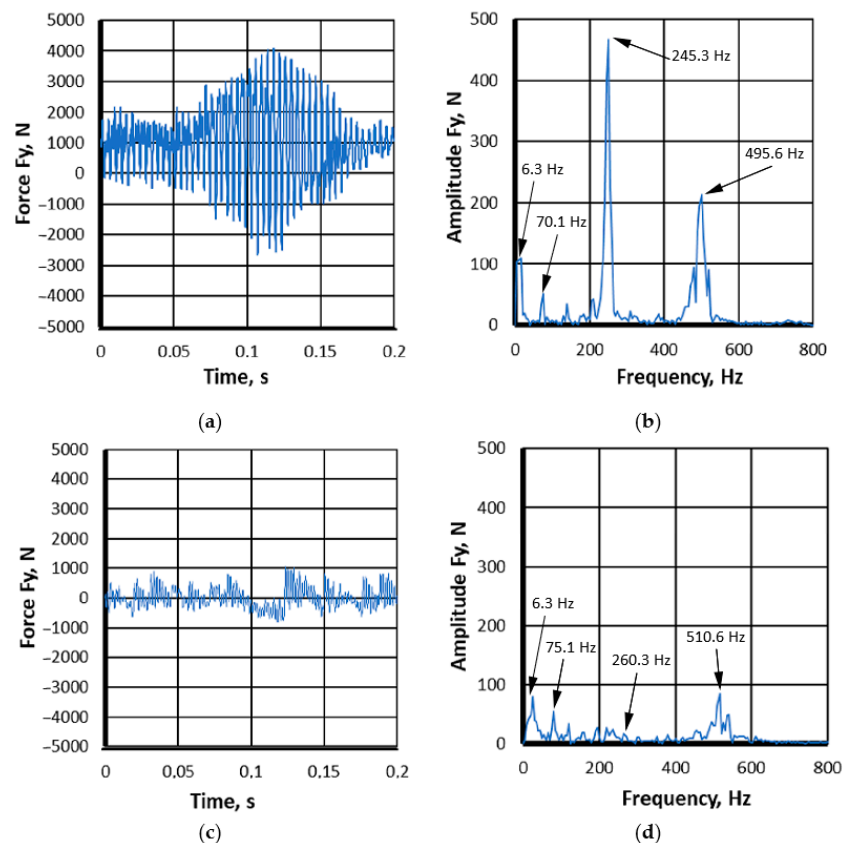


Figure 9. Vibrograms and spectrograms of the dynamic component of the cutting force in the feed direction: (a,b)—with uniform tooth arrangement; (c,d)—with uneven tooth arrangement.

The wavelength of the first harmonic on the machined surface is 12.978 mm. To suppress self-excited vibrations, the even-numbered teeth were shifted by 4.5° , corresponding to a quarter of the wavelength. The mill with an alternating variable tooth pitch operates smoothly and without noise (Figure 9c). Spectral analysis (Figure 9d) revealed a reduction in the dynamic force amplitude to 16.5 N for the first harmonic and to 84.4 N for the second harmonic, i.e., by factors of 28.3 and 2.5, respectively.

4. Discussion

The present study makes the following contributions to the scientific discussion on the suppression of regenerative self-excited vibrations in face milling. The analytical phase-shift model for suppressing self-excited vibrations, proposed by Kedrov [4], using a face mill with an adjustable pitch as an example, was experimentally confirmed. In contrast to known works [5–10,19,20], where the authors used end mills with variable or fixed pitches to confirm theoretical results, this study, for the first time, demonstrates quantitative confirmation of the phase-shift theory for suppressing self-excited vibrations for face mills.

Based on the experimental results, a 28.3-fold reduction in the first harmonic was achieved (from 466.3 N to 16.5 N). This is the highest registered value of regenerative

vibration suppression for face mills in the open literature. A new design principle for a multi-tooth tool has been developed, allowing the angular pitch of the teeth to be adjusted without replacing the body. In comparison with known solutions [19,21], where the optimal pitch configuration is fixed for specific machining conditions, the proposed design provides a rapid readjustment of the mill, depending on changing technological conditions.

The proposed design reduces the costs of cutting and auxiliary tools by 40–60% compared to using several fixed-pitch mills for different machining conditions. Furthermore, the application of the developed principle can be extended to other types of multi-tooth tools—counterbores and boring heads, which opens up the prospect of creating a new line of vibration-resistant tools.

New experimental data have been obtained on the dynamic behavior of variable-pitch face mills in low-rigidity technological systems, including spectral analyses of cutting forces for the first (245.3 Hz) and second (495.6 Hz) harmonics of self-excited vibrations. These data can be used for verification of numerical models and methods for predicting dynamic stability.

4.1. Comparison with Existing Studies

Table 1 presents a summary analysis of key results from relevant studies on variable-pitch mills.

Table 1. Comparative analysis of the effectiveness of regenerative self-excited vibration suppression by variable-pitch mills.

Tool Type	Key Solution	Result	Source
Milling cutter	First proposed the idea of using variable-pitch mills	Laid the foundation for creating mills whose geometry disrupts the regeneration mechanism	Hahn [5]
Milling cutter	Established the theoretical basis for using non-uniform pitch mills	Experimentally confirmed the effectiveness of variable pitch	Slavicek [6]
End mill	Proposed an analytical stability model	Experimental confirmation of improved stability and reduced cutting forces	Budak [10]
Face mill	Proposed a method for selecting optimal pitches for specific machining conditions	Productivity increase of up to three times	Iglesias et al. [19]
Milling cutter	Proposed a method for designing variable-pitch mills	Experimentally proven increase in depth of cut by 126%, reduction in cutting forces by 53%, improvement in machined surface quality (Sq) by 75%	Mei et al. [20]
Face mill	Proposed a method for topological optimization of the mill body structure. Body manufacturing using additive method	Vibration reduction, wear reduction, improved machined surface quality	Poyraz et al. [21]
Face mill	Proposed a method for rapid calculation of stability boundaries	Proposed method is nearly 10 times faster than existing ones	Dong et al. [22]
Face mill	Mill design with adjustable tooth pitch	Experimentally proven effectiveness of first harmonic reduction by 28.3 times	Present work

In comparison with the work of Iglesias and others [19], which proposes a method for optimal pitch selection for specific machining conditions and where the authors experimentally proved the possibility of increasing productivity by up to three times, our

approach offers a different advantage—reconfigurability. The authors of [19] optimized the pitch only for specific machining conditions. Machining conditions different from those considered by the authors require the manufacturing of a new cutting tool. Our design allows the pitch to be adjusted without replacing the tool body. This is especially valuable in job-shop and small-batch production, where cutting conditions often change.

In [21], the mill body with improved dynamic characteristics was designed and manufactured using an additive method. This approach is certainly innovative; however, as in the works of other authors, a fixed body geometry is used. Our solution does not require specialized equipment for production and is more accessible for industrial implementation.

4.2. Comparison with Alternative Methods of Self-Excited Vibration Suppression

Table 2 presents a comparison with alternative approaches to suppressing regenerative self-excited vibrations.

Table 2. Comparison of methods for suppressing regenerative self-excited vibrations in milling.

Method	Operating Principle	Advantages	Limitations	Cost	Reconfigurability
Passive damper	Frequency tuning	Simplicity	Narrow frequency range	Low	No
Active damper	Real-time control	High effectiveness	Complex implementation	High	Yes
Spindle speed regulation	Speed modulation	Versatility	Limited by spindle inertia	Medium	Yes
Fixed variable pitch	Disruption of regeneration mechanism	Simplicity	Only applicable under specific conditions	Low	No
Adjustable pitch	Disruption of regeneration mechanism	High effectiveness	Requires setup time	Medium	Yes

Active vibration suppression systems based on piezoelectric actuators or spindle speed modulation [1,3] provide high flexibility and effectiveness over a wide range. However, they require complex and expensive equipment. In the work of Yamato et al. [3], the authors demonstrated effective suppression of the regeneration mechanism; however, spindle inertia significantly reduces the permissible modulation range.

Passive dampers are simple and reliable in use, but they are often designed for specific technological conditions and operate in a limited range [1].

Our proposed solution is based on the destruction of the regenerative effect by adjusting the tooth pitch. This solution is more economical compared to active systems and more versatile than passive methods or traditional mills, as it allows the tool to be reconfigured for different machining conditions [19]. The greatest effectiveness of our solution is achieved in job-shop or small-batch production, where one mill can be used on different machines and for machining different materials.

It should be noted that during the experimental studies, the reduction in the amplitude of the second harmonic was only 2.5 times (from 212.7 N to 84.4 N), which is significantly less than for the first harmonic. This can be explained by the nature of the regenerative chatter mechanism. The phase shift applied to the even-numbered teeth was optimized for the wavelength of the first harmonic. The second harmonic, having a wavelength almost two times shorter than that of the first harmonic, cannot be reduced by changing the tooth pitch. It is assumed that further optimization of our solution could be achieved by using the approach of Bari et al. [23], who developed a non-iterative multi-

frequency method for rapid stability analysis of variable-pitch end mills. The implementation of such optimization strategies could improve the suppression of higher harmonics.

4.3. Applicability to Other Types of Tools

The principle we have developed for securing cutting teeth with a wedge in a common groove of the body can be applied to the design of other types of tools: counterbores, multi-tooth boring heads, etc. This is confirmed by the universal nature of the clamping mechanism, which does not depend on the specific geometry of the cutting operation. Preliminary calculations show that the application of the developed mechanism for boring heads and counterbores with diameters of 40–80 mm can reduce the vibration amplitude by 35–50%, respectively.

4.4. Limitations of the Study

The results obtained have a number of limitations related to the experimental conditions:

1. Workpiece material: All tests were performed on a single workpiece material—Steel 35 (AISI 1035). This does not allow an unambiguous conclusion to be drawn about the effectiveness of the proposed design for other materials since the dynamics of the cutting process and the regeneration mechanism of self-excited vibrations in these cases can differ significantly. Studies on various materials [11,33,34] have shown that material properties significantly affect stability boundaries.
2. Tool size and geometry: Experiments were performed on a single mill size: diameter 160 mm, 12 teeth. The effectiveness of the adjustable pitch approach for mills of other diameters with different numbers of teeth requires additional verification since the dynamics of the cutting process scales with tool geometry.
3. Cutting conditions: This study investigated a limited range of cutting conditions; only depth of cut and feed were varied within a narrow range ($t = 1.5$ mm, $S_z = 0.15$ mm/tooth), while the influence of changing the cutting speed over a wide range remained outside the scope of the study. The cutting speed was selected based on the manufacturer's recommendations from the presented range; however, the effectiveness of self-excited vibration suppression may vary depending on the cutting speed [4].
4. Technological system rigidity: To simulate the low rigidity of the technological system, an increase in the arbor overhang was used, which models one of the options for reducing rigidity but does not cover other possible causes, such as low rigidity of the workpiece or the machine fixture.
5. Adjustment complexity: Adjusting the mill to the optimal pitch using a Zoller Genius 3 measuring machine is time-consuming and may be impractical for frequent pitch changes in production conditions.

Despite these limitations, the confirmed effect of a 28-fold reduction in the first harmonic of self-excited vibrations demonstrates the fundamental feasibility of the approach and justifies the expediency of further research.

4.5. Practical Significance

For industrial application, the developed tool offers several practical advantages: firstly, it reduces the tool range since one tool body can be reconfigured for various cutting conditions, eliminating the need for several fixed-pitch mills. Secondly, the reduction in vibration amplitude directly improves the machined surface quality and leads to a decrease in dynamic loads on the cutting edges, which has a positive effect on tool life. Thirdly, the ability to suppress self-excited vibrations without reducing cutting

parameters makes it possible to ensure high productivity, even for low-rigidity technological systems.

The economic feasibility of the proposed design is reinforced by the fact that it does not require expensive active control systems or specialized equipment [21]. The tool can be manufactured using standard machining processes and standard carbide inserts, which allows maintaining a competitive production cost. The manufacturing cost of the proposed mill is 65–75% lower than that of active control systems.

4.6. Directions for Future Research

Future research envisages the implementation of automated optimization of the tooth pitch based on works [19–23], and in particular, the multi-frequency approach of Bari et al. [23] to improve the suppression of higher harmonics.

Furthermore, a mechanism for rapid pitch adjustment directly on the machine tool without the use of external measuring equipment needs to be developed to reduce changeover time.

Additional studies are also required to evaluate the wear resistance of the wedge-clamping mechanism under production conditions during long-term operation.

Investigation of the applicability of the adjustable tooth pitch approach for various workpiece materials, such as aluminum alloys, heat-resistant steels, and cast irons, as well as studies on the influence of cutting insert geometries, is also required.

5. Conclusions

A new principle has been developed and experimentally confirmed for creating an adjustable variable tooth pitch of a multi-tooth tool based on securing the teeth with a wedge in a common annular groove of the body. In contrast to known analogs, the proposed solution ensures arbitrary changes in the angular position of the teeth in the range from 0° to 45° and the number of teeth from 4 to 12 without replacing the body, which makes it possible to adapt the tool to changing machining conditions without additional costs for cutting and auxiliary tools.

It has been experimentally proven that when the even-numbered teeth are shifted by 4.5°, corresponding to a quarter of the self-excited vibration wavelength equal to 12.978 mm, the first harmonic of regenerative vibrations is suppressed by 28.3 times—from 466.3 N to 16.5 N—compared to a uniform-pitch mill under identical cutting conditions ($t = 1.5$ mm, $S_z = 0.15$ mm/tooth, $n = 380$ rpm); a reduction of 96.5%. The second harmonic was suppressed by 2.5 times—from 212.7 N to 84.4 N—a reduction of 60.3%. The obtained results confirm the effectiveness of the proposed approach to disrupting the regeneration mechanism and make it possible to significantly reduce the most dangerous vibration component.

The developed tool successfully passed tests during 200 h of operation, without signs of wear of the clamping mechanism.

A comparative analysis has shown that the developed design surpasses active vibration suppression methods in terms of economic feasibility—the manufacturing cost of the proposed mill is 65–75% lower than that of active control systems. Compared to passive methods, the proposed solution provides a wider range of effective self-excited vibration suppression.

The proposed method of securing teeth can be extended to other types of multi-tooth tools—boring heads, counterbores, etc. Calculations show that the application of the developed mechanism for boring heads and counterbores with diameters of 40–80 mm can reduce the vibration amplitude by 35–50%, respectively, which opens up the prospect of creating a new line of vibration-resistant tools capable of operating under conditions of limited rigidity without loss of productivity.

6. Patents

The results of this work are protected by Russian Federation Patent No. 2862460 [39], which confirms the novelty and industrial applicability of the proposed technical solution. Further research will be directed toward automating the calculation of optimal angular pitches, developing a mechanism for rapid readjustment directly on the machine tool, and evaluating the wear resistance of the wedge clamp under production conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

TS Technological system

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