Thin floor milling using moving support

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Abstract
During milling of the thin floor of a pocket which is located on a monolithic structure, it is very difficult to achieve high accuracy and good surface quality due to its low rigidity. In this paper, a novel approach is proposed to overcome the difficulties that are encountered during milling of the thin floor. The method is realized by using a small axial depth of cut but placing a moving support at the back surface of the thin floor during machining, in which the support will move with the cutter at the same velocity. An experimental platform is built to demonstrate the validity of the proposed method. The experimental results show that the proposed method can effectively improve the accuracy and surface quality of the thin floor of a pocket on the monolithic structure.

Keywords High-speed milling · Thin floor · Moving support · Robot-assisted machining · Pocket structure

1 Introduction
Flexible monolithic thin-walled workpieces with many pockets are widely used in engineering practice, especially in aerospace engineering. The multi-pocket structure is used to reduce the weight of the monolithic workpiece while maintaining its stiffness and strength [1]. Typical application of the multi-pocket structure includes the airplane fuselage and the rocket tank as shown in Fig. 1. The remaining wall thickness of the pocket, which refers to the normal distance from the outer and inner surfaces of the pocket after machining, is important as a compromise between the weight reduction and the strength. It becomes an important dimension requirement for the pocket structure. However, the cutting vibration and deformation, which are mainly caused by the low rigidity of the thin floor, will make it difficult to achieve desirable surface quality and accuracy after machining [2].

Usually, two different methods were employed to manufacture a flexible monolithic component with a multi-pocket structure as shown in Fig. 1. The processes of the two different methods are shown in Figs. 2 and 4, respectively. For the first one, the pocket structures are firstly machined by the high-speed milling process on a flat blank block which is usually fixed flatly on the worktable of a vertical machining center. Thereafter, the machined flat blank with a pocket structure is formed to the desirable shape by rolling or other metal-forming processes. For this method, the thin floor of a pocket is supported by the worktable surface. Hence, its stiffness along the axial direction of the milling cutter is strengthened during machining. The undesirable vibration of the thin floor along the axial direction is thus suppressed. However, rolling or forming flaws will easily occur due to uneven distribution of block workpiece materials because of the pocket structures, especially at the intersection part of several ribs. This makes the workpiece fail to meet the strict standard of the aerospace components. Besides, the axial depth of cut cannot be too large during milling of the thin floor since the remaining thickness of the floor will become thinner and thinner (as shown in Fig. 3) and even be cut
through due to the increasing axial depth of cut caused by the deformation of the floor under axial cutting force [4]. To avoid this, complex and expensive compensation methods were proposed to guarantee the thickness homogeneity of the thin floor [5, 6].

Different from the first method, the second one firstly forms the flat blank block to the desirable shape (Fig. 4). Thereafter, the pocket structure is machined on the formed blank to obtain the flexible monolithic component with a multi-pocket structure. Forming flaws that are encountered in the first method, especially those occurring at the joint part of several ribs, will be avoided since no pocket structure on the formed blank exists in the forming process for the second method. Henceforth, the second method is a promising method for manufacturing the flexible monolithic workpiece with a multi-pocket structure. However, the problem encountered in the second method is fixing the workpiece. The fixture has two intentions for this method, namely, to fix the workpiece and to reinforce the low stiffness of the thin floor to reduce the undesirable vibration during machining. However, after the blank is formed to the desirable shape, it becomes very difficult to clamp because of its complex surface. Besides, the inappropriate fixture condition may lead to the undesirable deformation of the formed blank before machining. The deformation will be released after machining and thus lead to severe dimensional or shape error of the final workpiece.

To resolve the fixation problem and thus clamp the workpiece properly for the second method, many solutions were presented in academia and engineering. A possible one was the so-called mold design method [7], in which a giant mold-like fixture whose inside surface has the same shape as the back surface of the workpiece (as shown in Fig. 5a) needs to be designed to support the flexible workpiece blank. Obviously, a large axial depth of cut should be avoided to eliminate the remaining thickness error of the thin floor as shown in Fig. 3. Besides, the mold-like fixture needs to be redesigned and reproduced for a workpiece with a different surface. Hence, it lacks flexibility. Sometimes, coatings, foams, or wax was used to replace the stiff material such as steel to fabricate the mold-like fixture [8]. Recently, Kolluru and Axinte [9, 10] proposed to use a novel ancillary device (as shown in Fig. 6) to reinforce the whole surface of the flexible workpiece blank during milling. The method consisted of distributed mass blocks, viscous tape, and torsion springs. The springs tensioned and placed in casing exert a radial force, acting as inertia force on casing. A conformable damping sheet such as neoprene pressed against the casing using the torsion springs provides stiffness during vibration of the casing due to stretching of the neoprene sheet between the springs. Moreover, the viscoelastic nature of the neoprene sheet provides damping to the casing. As a result, mass, stiffness, and damping are imparted to the thin wall structure without having the residual viscoelastic tape problem.

Aside from the mold design method, a multi-support method was developed as shown in Fig. 5b, in which several support elements or dampers were attached to some key locations (such as the locations that have the largest mode displacement of the workpiece) of the surface of a flexible workpiece which needs to be machined. This method can locally reinforce the stiffness of the workpiece. It is much
more flexible compared to the mold design method since the element of the multi-support method can be made as a matrix and the support location of every matrix element can be adjusted according to the workpiece surface. However, factors such as the number of the support elements, the layout of the support element, the applied force between the workpiece and the support element, and the sequence of the fixture operation need to be carefully considered for this method. Generally, it was treated as an optimization problem. For example, Qin et al. [12] analyzed and optimized the clamping sequence of the support elements by considering the varying contact force and friction force between the workpiece and the support elements during clamping. Chaari et al. [13] optimized the applied force of the fixture based on the particle swarm optimization (PSO) method. Chen et al. [14] optimized the layout and the applied force. A multi-objective model to reduce the maximum deformation and to increase the distribution uniformity of the deformation was established and solved by the genetic algorithm (GA). Sundararaman et al. [15] optimized the layout of the support elements with the surface response method. They modeled the relationship between the maximum workpiece deformation and the applied position. Yang et al. [16] also optimized the layout of the support element, but the method was based on the cuckoo search algorithm. Liu et al. [17] also optimized the number and the layout of support elements in the end milling process of the flexible workpiece. The optimization procedure consisted of two stages. The first stage was to place the support elements at the positions with local maximum deformation. Thereafter, the number of the elements was reduced by a specified optimization method. Zeng et al. [18] also introduced a design method which can

Fig. 3  Simplification of the thin floor machining (a) and the remaining thickness after one path of milling (b)

Fig. 4  The second method to manufacture large monolithic components with multi-pockets
optimize the element location, the applied force, and the element number simultaneously.

For the multi-support method, it can locally increase the stiffness of the workpiece at some key locations. However, the axial depth of cut can be neither too large nor too small when the cutter is located at the area between two support elements. If the axial depth of cut is too large, the remaining thickness of the floor will become thinner and thinner and even be cut through as shown in Fig. 3. On the other hand, if the axial depth of cut is too small, vibro-impact will occur between the floor and the cutting tool due to the separation in between and thus lead to poor surface quality [19, 20]. Moreover, it will take much time to clamp the workpiece. In addition, it is a difficult task to control so many fixture elements simultaneously.

As discussed above, the mold design method aims to support the whole back surface of the workpiece while the multi-support method aims to support the workpiece back surface at some key points with fixed elements. Different from these two methods, a novel method, which employs only one moving element to support the back surface of workpiece, is proposed in this investigation. The remaining parts focus on the principle, details, and realization of the proposed method. Specifically, Sect. 2 illustrates the principle and details of the newly proposed method. The difference between the proposed method and the existing ones is also discussed in this section. Section 3 describes the realization of the proposed method and the validation of the proposed method by conducting experiments. Section 4 discusses the experimental results obtained using the proposed method while Sect. 5 gives a summary of major contributions of this investigation.

2 Proposed method and its model

The schematic diagram of the proposed method is shown in Fig. 7. A small axial depth of cut $a_p$ (much smaller than the remaining thickness of the thin floor) is chosen to eliminate the error of the remaining thickness of the thin floor as shown in the Fig. 3. To avoid the separation between the floor and the cutting tool, a moving support element is placed at the back surface of the thin floor. The axis of the support element will be collinear with the axis of cutting tool. During milling of the floor, the support element will move with the cutting tool at the same velocity, and the two axes will keep aligning with each other in the whole milling.
process. The proposed method is similar to the one which was proposed by Shamoto et al. [21, 22]. It is called double-sided milling which utilized a right and a left face milling cutter to machine both sides of a thin plate simultaneously. Recently, Fei et al. [23, 24] proposed to use a moving fixture to suppress the chatter vibration and workpiece deformation while Ozturk et al. [25] proposed to use a moving support to increase the production during machining. However, the method proposed in their investigations was mainly used for thin wall machining.

During machining of the thin floor, it will vibrate easily because of its low stiffness. If the vibration displacement of the floor at the zone of the cutter tip is larger than the small axial depth of cut, the cutter will separate from the floor; when the floor vibrates back, it will collide with the cutter and then the vibro-impact occurs, which will make serious damage to the machined surface quality [26]. After a moving fixture element is used to support at the back surface of the workpiece, the vibration of the floor will be effectively prevented, as well as the contact loss between the floor and the cutter. The vibro-impact between the workpiece and the cutting tool can therefore be suppressed. Besides, the moving support will reinforce the local stiffness of the workpiece and thus improve the system stability, which will result in better surface quality. The moving fixture will also decrease the floor deformation effectively, and thus decrease the form error.

Differences between the proposed method and the existing multi-support methods are the following: (i) the fixture element is moving for the present method while it is fixed for the existing methods; (ii) only one fixture is needed while more than one element are needed for the existing methods. The advantages for the present method include the following: (i) the cost will be smaller than that of the existing method because fewer support elements are needed; (ii) the vibration and deformation will be decreased effectively because of the simultaneous movement of the fixture element with milling tools, unlike in the multi-support system, where chatter and deformation still exist in the zone between two adjacent support elements. Besides, the present method will cost less clamping time when compared to the multi-support method.

However, it is not easy to let the cutter axis align perfectly with the support element axis, which may lead to a distance between the two axes and thus lead to the twist of the thin floor as shown in Fig. 8. To solve this problem, the present investigation has designed a support head which will be presented in the next section to remove this twist effect. The contact force between the support head and the floor is also very important. The contact force between the support head and the thin floor can be neither too large nor

![Fig. 7 The schematic diagram of the proposed method](image)

![Fig. 8 Twist caused by the non-coaxial alignment between the milling force and the support force](image)
too small. If it is too large, there will be scratches on the back surface of the thin floor. Conversely, if it is too small, the floor will still separate from the cutter. The following section will focus on the experimental setup based on the abovementioned method.

3 Experimental validation

3.1 Experimental setup

An experimental setup is built to realize the proposed method. The setup consists of two five-degree-of-freedom (DOF) parallel robots where one is equipped with a milling head while the other one is equipped with a support head. Instead of using a giant serial machine tool and support unit to realize the proposed method to machine the pocket structure of a monolithic workpiece, a compact parallel or hybrid robot with 5 degrees of freedom with high rigidity, dynamic response, and light weight can be cost-effective. In addition, the robot can be built as a module and placed on a reference guide to move to the place where the pocket needs to be machined, which is especially suitable for the manufacturing of the monolithic workpiece. A successful application is the Tricept robot and Exechon robot. The CAD model of the setup is shown in Fig. 9.

The milling robot used in the setup is called TriMule, which was developed by Huang et al. [27, 28]. It is a new type of hybrid robot. Its configuration is similar to the Tricept robot and Exechon robot while it combines the advantages of the Tricept robot and Exechon robot. Namely, the accuracy of its end effector can be guaranteed through dual closed-loop feedback control. The direct kinematics of the TriMule can be solved analytically. A significant potential advantage of the TriMule over the Tricept arises because all the joints connecting the base link and the machine frame can be integrated into one single, compact part, leading to a lightweight, cost-effective, and flexible design particularly suitable for configuring various robotized manufacturing cells [27, 29]. The real milling robot and its corresponding mechanism schematic diagram are shown in Fig. 10. From the figure, it can be seen that the TriMule robot consists of a 1T2R spatial parallel mechanism plus an A/C-type wrist.

The spatial parallel mechanism can be treated as a 6-DOF UPS limb plus a 2-DOF planar parallel mechanism which is composed of two actuated RPS limbs and a passive RP limb in between with its one end being rigidly fixed to the platform. The base link of the planar parallel mechanism is connected by a pair of R joints with the machine frame. Here, R, P, U, and S denote revolute, prismatic, universal, and spherical joints, and the underlined P means an actuated prismatic joint, respectively.

The dimension of the robot machining center is shown in Table 1. The workspace of the milling robot is shown in Fig. 11. The tool interface of the spindle is HSK-E40, with the highest spindle speed of 24,000 rpm, a power of 7.5 kW, and a torque of 7.2 N m.

![Fig. 9 The CAD model of the proposed method](image)

![Fig. 10 The milling robot and its mechanism schematic diagram [29]](image)

| Table 1 | Dimensional parameters of the robot (in meters) |
|---------|-----------------------------------------------|
| $a$ | 0.135 |
| $b_1$ | 0.320 |
| $b_2$ | 0.570 |
| $e$ | 0.345 |
| $l_1$ | 0.120 |
| $l_2$ | 0.220 |
| $d$ | 0.190 |
| $H$ | 1.000 |
| $h_1$ | 0.240 |
| $h_2$ | 0.220 |
| $R$ | 0.620 |
The support robot is obtained by replacing the milling head of the machining robot with a support head. The real device and the corresponding schematic diagram of the support head are shown in Fig. 12. The key parts of the support head [30] are the seven balls as shown in the figure. One of the balls is located at the center of the sleeve. The central ball is integrated with an ultrasonic thickness measurement sensor to measure the remaining thickness.
of the thin floor. The rest of the balls are distributed aver-
egely around the center one. The aim is to suppress the
twist effect of the workpiece caused by the non-coaxial
alignment of the cutter axis and the support head axis as
shown in Fig. 8. All the balls have a diameter of 15 mm.
Each universal ball is fixed on the head of a piston rod of
a small pneumatic cylinder. The small pneumatic cylinder
at the back of each ball makes the ball have a small dis-
placement along the axial direction of the cylinder, which
allows the support to be applied to the workpiece with a
curved surface.

The control structure of the whole experimental setup is
shown in Fig. 13. The whole control structure is composed
of the master control system and the slave control system.
The master control system, which is used to control the mill-
ing head, is divided into the motion control of the robot and
the spindle control, respectively. The cutting path will be
generated by the master control system [31, 32]. The fol-
lowing path of the support head is obtained according to the
cutting path by considering the workpiece thickness. The
motion control and support control are realized by control
of the joint variable of the support robot, which is solved
according to the inverse kinematics.

The real experimental platform is built according to the
CAD model and the above described control principle, as
shown in Fig. 14.

3.2 Cutting conditions

To verify the effectiveness of the proposed method, a
cutting test is implemented on the developed platform.
For simplicity, a planar workpiece with dimensions
1000 mm × 1000 mm × 15 mm is utilized during machining.
Two edges of the workpiece at opposite side are clamped.
The workpiece material is aluminum alloy 6061.

A triangular pocket as shown in Fig. 15 is machined at
the center of the planar workpiece. During the machining
process, acceleration sensors are attached to the back surface
of the workpiece to measure the acceleration signals, which
will be used to analyze the generation of the chatter during
milling (Fig. 16). Two acceleration sensors are used in total
during the cutting test. Considering the interference between

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Fig. 13 The control structure of the whole system
the moving support head and the acceleration sensors, the acceleration sensors are placed at the area of the back surface of the plate that is near the cutting zone. Since the workpiece is too large that it cannot be fixed on the dynamometer, the machining force signals are not taken in this investigation. After the machining is finished, the machined surfaces are detected.

The cutter used in the machining process is a right-hand cutter with a diameter of 16 mm and 3 flutes. The helical angle of the cutter is 50°. The material of the cutter is hard steel. The total length of the cutter is 80 mm. The cutter is clamped with the overhang equal to 25 mm. Cutting tests are conducted on the workpiece with and without a moving support by using the parameters listed in Table 2. The cutting parameters listed in the Table 2 are chosen through a trial cutting experiment. The trial cutting results show that chatter will occur during milling of the planar workpiece using the cutting parameters listed in Table 2 without support. The cutting path used in the tests is shown in Fig. 15.

3.3 Experimental results
3.3.1 Chatter vibration

Figure 17 shows the acceleration signals during machining of the thin floor of the pocket structure with and without a moving support. From the figure, it can be seen that the amplitude of the acceleration with a moving support is much smaller than that obtained without a support. Besides, the signals are much smoother for the case with a moving support. The FFT (fast Fourier transform) of the signals is shown in Fig. 18. The main frequency part of the acceleration signal under a moving support is the tooth passing frequency which is \( f = 234 \) Hz and its integer multiple, which means that the cutting process is stable. The FFT of the signal under the case without support is rather different, except the passing frequency part; other parts like \( f = 341 \) Hz and \( f = 420 \) Hz also exist, which means that the cutting process is unstable and chatter occurs.
3.3.2 Surface quality

The machined surface under different milling conditions (with and without support) is shown in Fig. 19. From the figure, it can be seen that the surface quality with the moving support is much better than that without support. The surface roughness $R_a = 1.3414 \, \mu m$ for the case with a moving support while it is $R_a = 4.0135 \, \mu m$ for the case without support. This demonstrates the effectiveness of the proposed method to obtain a thin floor with high accuracy during machining of the pocket structure.

### Table 2 The cutting parameters used in the cutting tests

| Axial depth of cut (mm) | Radial depth of cut (mm) | Spindle speed (rpm) | Feed velocity (mm/min) |
|------------------------|-------------------------|---------------------|------------------------|
| 0.5                    | 5                       | 5000                | 2000                   |

### 4 Discussion

Acceleration signals are measured during milling of the thin floor with and without a moving support. The acceleration signals in time domain are shown in Fig. 17. It can be seen from the figure that the amplitude of the acceleration when milling without support is much larger than that with support. Fourier transformation results of corresponding acceleration signals in time domain are shown in Fig. 18. It also shows the fact that the amplitude of the acceleration that is obtained without support is larger than that obtained with support. The introduction of the moving support increases the dynamic stiffness of the whole system which can be denoted as $(K - M\omega^2 + Cj\omega)$, where $M$, $C$, and $K$ mean the system mass, damping, and stiffness matrix, respectively. The amplitude of the Fourier transformation of the displacement which is $|X(j\omega)| = |(K - M\omega^2 + Cj\omega)^{-1} * F(j\omega)|$ will decrease due to the increase of the dynamic stiffness. And thus the decrease amplitude...
of the Fourier transformation of the acceleration signals $|A(j\omega)| = |-\omega^2 * X(j\omega)|$. Besides, it can be seen from the FFT that chatter occurs during milling of the thin floor without support since some other frequency components that are not tooth passing frequency exist, while the chatter is successfully suppressed during milling with moving support. This can also be demonstrated by the machined surface topography as shown in Fig. 19, in which irregular marks are shown during milling without support while for the case of using support, only regular cutting marks are observed.

This investigation proposes to use the moving support to strengthen the local stiffness of the thin floor during its milling process and is successfully realized by two robots. The experimental results also show the validity of the proposed method. However, the following aspects about the proposed method remain to be solved and should be studied in depth in the future investigation:

- How to control the contact force still remains a major challenge. The contact force between the support element and the thin floor cannot be too large or too small. If it is too large, there will be scratches on the back surface of the thin floor. If it is too small, the cutter and the floor will still be separated. Recently, the authors tried to use the air jet as the moving support.
- How to choose a proper axial depth of cut is also a challenge. The axial depth of cut cannot be too large or too small. If it is too large, the floor will become thinner and thinner. If it is too small, the production will be limited.

The proposed method in this investigation is suitable for machining the flexible monolithic workpiece with pocket structures such as wings, skins of the airplane, and the fuel tank of a rocket. As to some flexible workpieces with a limited workspace such as impellers, collision will become an obstacle during machining for the proposed method, which should be
taken into consideration during design of the support head as well as the milling head. This is also the limitation of the proposed method.

5 Conclusions

This paper proposes a novel method to machine the thin floor of a pocket structure. The method is realized by placing a support at the back side of the workpiece. During the milling process, the support will move with the cutting tool at the same velocity. Based on this idea, an experimental setup is constructed. It is composed by two five-degree-of-freedom robots where one is equipped with a milling head while the other is equipped with a support. A novel support device is designed to avoid the workpiece twist caused by the non coaxial alignment of the cutter axis and the support axis. Cutting experiments are implemented on the newly built experimental setup. The experimental results showed that the chatter during milling of the thin floors of the pockets can be suppressed by the developed novel system. Besides, the surface quality of the floor is much better than that obtained by the traditional machining method. All these demonstrate the validity of the proposed method.

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Declarations

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