Increase of horizontal stiffness for fixing mobile machine with vacuum pad by using filament tapes

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Abstract. This paper presents a method to increase fixing stiffness of mobile machine by using filament tapes. Mobile machine moves on a large workpiece for cutting, drilling, welding, and cleaning, etc., so for those works. The vacuum pads are generally used for attaching or detaching objects frequently. Of course, if the object is a metal body, the magnetic force can be used. The vacuum pads have an advantage that it can be used regardless of the magnetic property of the object, but it has a disadvantage that the fixing stiffness is not strong because the material is rubber. That’s why it is difficult to maintain the accurate position of the mobile machine as it could be shaken when being moved or fixed. Thus, this study proposed a method to increase the horizontal fixing stiffness of the mobile machine by using filament tapes to the side of the vacuum pads which compensate the shortcoming of the vacuum pads. Filament tapes are made by inserting special material filaments which have high rigidity into an existing tape to increase tensile strength. In the configuration of the proposed method, the vacuum pad forms the vertical fixing stiffness by suction force, and the filament tape forms the horizontal fixing stiffness by adhesive force. In order to verify the effectiveness of the proposed method, the experimental equipment to measure the fixing stiffness was fabricated, and the comparison experiment was carried out. First, the horizontal fixing stiffness of the vacuum pads and the filament tape was measured respectively as a baseline data, and then the same measurement of the combination of them was performed for the comparison. In addition, another experiment for comparison between Gecko films and filament tape was performed. The results showed that the horizontal fixing stiffness was significantly increased when the filament tape was used together with the vacuum pads, and the Gecko film was not as much effective as the filament tape in terms of the strength of the stiffness. On the other hand, the filament tape needs to be replaced with a new one after several times use. So we developed the automatic filament tape supplier and examined its applicability through experiments.

1. Introduction
In conventional machining, a machine is larger than parts, so most parts are processed in the machine fixed at. However, in the case of large workpieces such as aircraft fuselages, aircraft wings, ships, etc., it may be difficult to process them by conventional methods. Usually the size of the machine should be more than twice the size of the workpiece. Considering manufacturing cost, installation space, and maintenance, equipping such a large processing machine is not only economically inefficient but also there are many things to consider technically such as static and dynamic characteristics of the mechanical structure. In order to overcome these limitations, a different machining method than the
conventional method was required, and research on a mobile machine in which a workpiece is fixed and a machine moves on a large workpiece has been conducted by a number of researchers[1~4].

![Figure 1. Mobile machine on machining on site.](image1)

![Figure 2. Multi-collaborative machining.](image2)

Figure 1 shows that a mobile machine is directly machining in the field on large workpieces. Figure 2 shows that several mobile machines collaborate together on a large workpiece. As can be seen from figures 1 and 2, the mobile machine can be used to perform operations such as drilling, milling, welding, riveting, inspection, etc., while moving on a large workpiece. In order to perform such tasks, the mobile machine must execute walking and stopping repeatedly on a large workpiece. In this case, using any device for fixing the mobile machine is essential. If a large workpiece is a metal body, it may be able to fix the mobile machine by using magnetic force. In opposition, if the large workpiece is a non-metal body, it is common to use a vacuum pad as the magnetic force cannot be used. Vacuum pad has an advantage that it can be used regardless of the material of the workpiece, but it has a drawback that the horizontal rigidity is weak because the material is rubber. This can make it difficult to keep the position of the mobile machine precisely because it can be shaken when the mobile machine is fixed on the workpiece.

Therefore, in this study, we proposed a method to increase horizontal stiffness of a device for fixing a mobile machine by adding filament tapes to compensate the weak horizontal stiffness of vacuum pads. The filament tape is made by inserting filaments of special material of high tensile rigidity into the tape. When a filament tape is used together with a vacuum pad, the vacuum pad has the suction force forming the vertical fixed stiffness, while a filament tape has adhesive force forming the horizontal fixed stiffness. By adding the filament tape to the vacuum pad, the position error of the mobile machine can be reduced. To verify the effectiveness of the proposed method, an experimental equipment was fabricated and tested. First, the horizontal fixed stiffness was measured for each of the vacuum pads and the filament tapes, and then the same measurements were carried out in a state in which these were combined and then compared with each other.

Experimental results showed that the use of the filament tapes with vacuum pads resulted in significantly higher horizontal fixed stiffness than using only vacuum pads. For comparison, the same experiment was performed on the Gecko film. The rigidity of the Gecko film was not as much effective as the filament tape. On the other hand, the filament tape has to be replaced with a new tape when it is used many times. Therefore, a device which automatically supplies the filament tape has been developed to eliminate such inconvenience, and the applicability has been confirmed through the experiments.

2. Experimental System

2.1. Design of experimental apparatus for measuring horizontal stiffness of mobile machine

In this study, we proposed a method of adding a filament tape to reinforce the horizontal stiffness of a vacuum pad. Therefore, an experimental apparatus was designed and fabricated to examine the effectiveness of the proposed method. Figure 3 is the three-dimensional conceptual diagram for
explaining the configuration of the experimental apparatus. Eight vacuum pads having a diameter of 80 mm were mounted. On the inner side, four filament tapes having a contact area of 90 mm * 40 mm were mounted. Figure 3 shows that the vacuum pad creates the vertical stiffness of the fixing device of the mobile machine, and the filament tape increases the horizontal stiffness of the fixing device. Such a configuration may be effective in reducing the linear and rotational motion errors of the mobile machine. Figure 4 shows the location of the vacuum pads and filament tapes on the bottom of the device for fixing the mobile machine.

![Figure 3. Concept of experimental apparatus.](image)

![Figure 4. Bottom view of the apparatus.](image)

2.2. Configuration of experimental apparatus

Figure 5 shows the experimental apparatus fabricated. It shows the set-up state to measure the horizontal fixed stiffness of the fixing device of the mobile machine. Vacuum pads are moved up and down to correspond to the height of the workpiece surface and are possible to be tilted so that the vacuum pads could be vertically aligned with the curved surfaces of the workpiece. The preparation of the horizontal stiffness measurement of the device is as follows. The experimental apparatus was placed on the workpiece and connected to the vacuum line. The vacuum pads and filament tapes were attached to the workpiece surface. A screw type drive unit was installed to apply a horizontal force to the device. Between the screw type drive unit and the fixing device of the mobile machine, a force measuring sensor was installed to measure the force applied to the fixing device. When a force is applied to the fixing device, displacement occurs. In order to measure this displacement, a displacement measuring sensor was placed in front of the fixing device. Figure 6 shows the bottom view of the experimental apparatus where there are the vacuum pads, filament tapes, and gecko films.

![Figure 5. Experimental apparatus set up.](image)

![Figure 6. Experimental apparatus (Bottom view).](image)
To measure the horizontal stiffness of the Gecko film, Gecko films were added to the filament tapes to make the experiment possible.

3. Experiments and considerations

3.1. Experiment method and contents

The validity test of the proposed method was performed by using the experimental equipment manufactured in this study. First the surface of the table was cleaned, then the test device was placed and the vacuum line was connected to the test device. When a proper vacuum pressure (~0.8 bar) is produced, the screw type drive unit was used to apply a horizontal force to the mobile machine's fixing device. At this time, force and displacement are simultaneously measured by the force sensor and the displacement sensor. Subsequently, the screw type drive unit was used to increase the horizontal force on the fixing device and measure the force and displacement. Such an experiment was repeated until the fixing device is removed off from the table surface.

3.2. Results and discussions

Figures 7 and 8 show the measurement of the displacement at that time while applying a horizontal force to the fixing device of the mobile machine. Figure 7 shows that the horizontal stiffness increased by more than 8 times when the filament tape was used together with the vacuum pad. It was shown that the measurement result, when the filament tape was used only, does not have significant difference with the case where the vacuum pad is used with the filament tape. It can be said that most of the horizontal stiffness of the fixing device of the mobile machine is covered by the filament tape. As described in the introduction, it has been demonstrated that the vacuum pads are involved in forming the vertical stiffness of the mobile machine's fixing device, and the filament tape is involved in forming the horizontal stiffness. Therefore, it would be advantageous to use a filament tape together with a vacuum pad to reduce the fixed error of the mobile machine. Figure 8 shows the results of experiments using Gecko films instead of filament tapes. Compared with the stiffness of the filament tape, the Gecko film does not greatly contribute to the increase in rigidity. The reason is that the filament tape depends on the bond adhesion, but the Gecko film is dependent on the atomic attraction.

![Figure 7. Displacement vs load with filament tape.](image1)

![Figure 8. Displacement vs load with Gecko film.](image2)

In each of the above experiments, the cases in which the mobile machine's fixing device deviate from the table surface without being able to overcome the horizontal force are as follows. It is the case of a vacuum pad which slips due to the limit of frictional force between the table surface and the vacuum pad. It is the case of filament tape of which the adhesive layer fails to overcome the adhesive
shear force on the tape surface. And it is the case that the atomic attraction of Gecko film reaches a critical point. The filament tape used in the experiment has an available contact area of 90 mm * 40 mm with the surface of the workpiece. However, all the area of the filament tape was not involved in the horizontal resistance when examined in the experimental procedure. As can be predicted from Figure 6, the filament tape resisted the horizontal force only in the form of a line with a tape width of 40 mm at the portion of the tape supporter. Therefore, it can be considered that if a plurality of payload rollers such as a wheel of a tracked vehicle are installed to press the tape, it will have much stronger horizontal resistance than the results of the experiment. In this experiment, the tensile strength of the filament and the properties of the pressure-sensitive adhesive were not examined. This is, under the same conditions, because the purpose was to compare the change in horizontal fixing stiffness when the vacuum pad alone was used and when the filament tape was used together with the vacuum pad. Therefore, a filament tape which is widely used in daily life was selected and used in the experiment. If larger horizontal stiffness is desired in a smaller area, it may be helpful to select a tape containing a larger tensile strength filament or a higher shear adhesive. It is also possible to vary the horizontal fixing stiffness of the device through the use of the same filament tape and varying the contact area.

4. Filament tape automatic supplier

![Figure 9](image.png) Concept design of automatic supplier.

![Figure 10](image.png) 3D view of automatic supplier.

![Figure 11](image.png) Automatic supplier.

In the method proposed in this study, the filament tape is dirty when used many times, and the adhesive layer is disturbed. Therefore, we have to change the tape at the right time. So we have developed a device that automatically changes the filament tapes. Figure 9 shows the automatic feeding method of the filament tape, and Figure 10 shows its three-dimensional conceptual diagram.
Figure 11 shows the automated filament tape feeding system. The filament tape is wound on a tape roller. If you turn the tape roller together while turning the tape rewinder, you can replace them with new tape. When the up-down cam is turned, the tape supporter moves up and down to attach or detach the tape to the surface. This series of operations is performed entirely simultaneously.

5. Conclusion
In this paper, we proposed a method to increase the horizontal fixing stiffness of a mobile machine by adding a filament tape to a vacuum pad. To verify the effectiveness of the proposed method, an experimental equipment was fabricated and tested. Experimental results showed that the horizontal fixing stiffness is significantly increased when the filament tape is used together with the vacuum pad. In addition, a device for automatically feeding filament tape was developed, and its applicability was confirmed.

6. References
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