Development of High-precision Gear Hobbing Machine for Small-module Gears Used for Precision Reduction Gears

KAZUYUKI ISHIZU[*1] SHINGO TAKADA[*2]

In recent years, robot technology has advanced remarkably and the introduction of industrial robots is accelerating in order to reduce labor and automate factory lines. With such a background, the demand for precision reduction gears used for robot articulations has been increasing, and the production volume of small-module and high-precision gears used inside precision reduction gears is expected to increase.

In the industrial robot market, which will continue to grow, highly-precise reduction gears are required in order to improve the performance of robots. Therefore, there is a need for equipment that can machine gears to be used inside reduction gears stably with high accuracy and high efficiency. Mitsubishi Heavy Industries Machine Tool Co., Ltd. has developed the GE15FRplus gear hobbing machine, which can realize high-precision and high-efficiency machining to meet this need. This report presents the features and machining examples of this gear hobbing machine.

1. Introduction

Small-module gears for precision reduction gears are used in planetary reduction gears and strain wave reduction gears. **Figure 1** shows the features of planetary gears and strain wave gears. A planetary gear revolves around the sun gear located in the center of the reduction gear while rotating. On the other hand, a strain wave gear is used in a reduction gear that uses a differential between an ellipse and a perfect circle and a thin cup-shaped metal elastic gear is used inside the reduction gear. The gear machined on the outer periphery of the opening engages with the internal gear of the mating part to transmit power. Since strain wave gears have a thin cup shape, they are easily deformed during gear machining and the required accuracy is higher than that of planetary gears.

This report introduces high-precision and high-efficiency hobbing technology for strain wave gears that achieves the required accuracy.

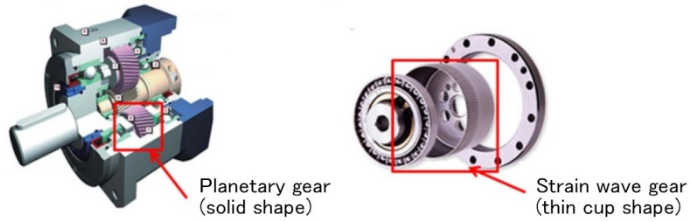
2. Features and required accuracy of strain wave gears

Mainstream strain wave gears have a module of 1.25 or less and 100 to 200 teeth and the required accuracy of ISO class 3 or higher. Reduction gears used for robot articulations are required to have a high indexing accuracy and suppression of torque fluctuation during rotation. For this reason, among gear accuracies, the pitch accuracy of strain wave gears inside reduction gear in particular must be improved.

However, the thin cup-shaped opening is easily deformed during gear machining, which makes it difficult to ensure the required accuracy. Furthermore, it is difficult to use gear grinding because the module is so small that the manufacture of the grinding wheel is difficult and profile grinding is inefficient. In addition, since there are many gear teeth, productivity improvement requires the realization of high-precision and high-efficiency machining with a hobbing machine that uses generation grinding rather than profile grinding.

*1 Engineering Manager, Engineering Headquarters, Mitsubishi Heavy Industries Machine Tool Co. Ltd.
*2 Chief Staff Manager, Engineering Headquarters, Mitsubishi Heavy Industries Machine Tool Co. Ltd.

Small-module gear for precision reduction gear



Planetary reduction gear
Source: TAIYO, Ltd. website

Strain wave reduction gear
Source: Harmonic Drive Systems Inc. website

		Small-module gear for precision reduction gear	
		Planetary gear	Strain wave gear
Module		2 or less	1.25 or less
Number of teeth		50 or less	100 to 200
Shape		Solid	Thin cup
Required accuracy	ISO standard	Class 5	Class 3
	Single pitch accuracy	4.7 μm*	2.5 μm*
	Cumulative pitch accuracy	11 μm*	7 μm*

* Values when module is 0.5

Figure 1 Features of planetary gears and strain wave gears

3. Development of hobbing machine specialized for machining strain wave gears

In order to achieve the machining of both higher-precision and higher-efficiency strain wave gears with a hobbing machine, high-speed and high-feed machining with reduced cutting force is required. However, our GE15A hobbing machine can machine gears with up to 4 modules. It is also suitable for heavy cutting and is mainly intended for cutting solid materials. The GE15A has a hob cutter diameter of ϕ 32 mm, a cutting speed of 200 m/min and a maximum cutting force of 3500 N and also features a machining accuracy of ISO class 5. Its maximum hob spindle rotation speed is 2000 min^{-1}, its maximum table axis rotation speed is 300 min^{-1} and its structure can withstand the maximum cutting force, using four rows of angular bearings and cylindrical roller bearings for the hob spindle and the table axis, respectively. However, this hobbing machine is not suitable for machining strain wave gears.

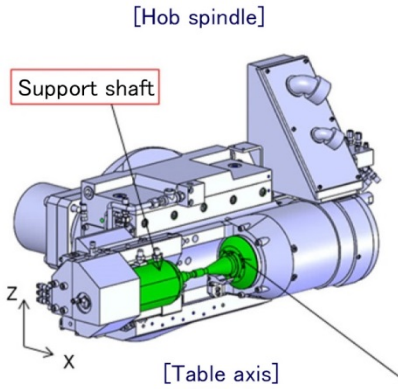
Therefore, for machining strain wave gears, we have developed the GE15FRplus high-precision hobbing machine for small-module gears. This machine has a hob cutter diameter of ϕ 32 mm and achieves machining accuracy of ISO class 3 (single pitch accuracy 2.5 µm, cumulative pitch accuracy 7 µm) under high-speed and high-feed conditions at a cutting speed of 800 m/min. **Figure 2** presents an external view and the mechanical specifications of the GE15FRplus hobbing machine, including the features of the hob spindle and table axis. The maximum rotation speed of its hob spindle is 8000 min^{-1}.

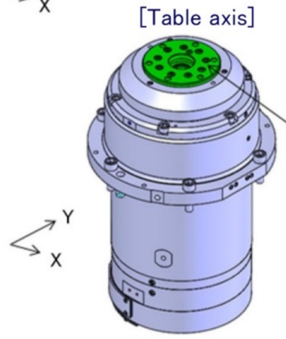
3.1 Higher-speed and higher-precision hob spindle

The challenges with the higher-speed and higher-precision hob spindle include the reduction of spindle vibration and heat generation due to the increase in rotation speed. The cutting force during machining a strain wave gear is as small as several tens of newtons and its effect on vibration and heat generation is minimal.

First, the hob spindle configuration was determined by simulating the hob spindle shape, the layout of the high-speed bearings and the necessary support rigidity so that the primary critical speed would be 1.2 times or more than the specified rotation speed of 8000 min^{-1}. Next, in order to improve the rotational runout accuracy of the hob cutter on the machine, the hob cutter was fastened to the double-supported hob spindle via a two-face constrained HSK arbor. One of the advantages of the HSK interface is that it can prevent the hob cutter from being pulled in the axial direction when the hob spindle rotates at a high speed and the taper part is centrifugally expanded.

A direct drive motor was adopted as the drive system in order to eliminate the non-linear elements of the rotating shaft from the rotating axis system. In addition, the inertia was reduced to suppress the excitation force due to unbalance and balance correction faces were provided on both sides of the motor to allow adjustment during assembly so that unbalance can be removed.





		GE15FRplus	GE15A
Maximum workpiece diameter		150 mm	150 mm
Maximum cutting module		1.25	4
Hob spindle	Maximum rotation speed	8000 min^{-1}	2000 min^{-1}
	Drive mechanism	Direct drive	Gear train
Table axis	Drive mechanism	Direct drive	Gear train
	Position detection	High-precision encoder	Pulse coder
	Control	Full-closed loop	Semi-closed loop

Hob spindle
- ✓ High-speed bearing arrangement
- ✓ HSK interface
- ✓ Direct drive motor
- ✓ Unit balancing
- ✓ Bearing cooling

Table axis
- ✓ Direct drive motor
- ✓ High-precision encoder
- ✓ Low-cogging torque motor
- ✓ Non-contact seal

Figure 2 External views and mechanical specifications of GE15FRplus hobbing machine, including features of hob spindle and table axis

Furthermore, as a countermeasure against heat generation in the hob spindle bearings and motor, coolant synchronized with the machine temperature was circulated near the heat source. As a result, the temperature increase of the hob spindle was suppressed and the adverse effect on machining accuracy was eliminated.

Consequently, a higher-speed and higher-precision hob spindle was achieved. The hob spindle rotational vibration amplitude measured at a point near the hob spindle bearing is 1 μm$^{P\text{-}P}$ or less at a rotation speed of 8000 min^{-1}, the non-repetitive runout (NRRO) of the hob spindle is 0.5 μm or less and the hob spindle end face runout is 1 μm or less. **Figure 3** illustrates the vibration amplitude near the hob spindle and the Lissajous waveform of the hob spindle.

3.2 Higher-precision table axis

The pitch accuracy of strain wave gears depends on the non-repetitive runout of the table rotation axis. In order to achieve high accuracy, an axis system configuration that takes rotational accuracy into consideration more than the hob spindle is necessary.

The table axis of the GE15A has a gear train structure and is semi-closed loop controlled. On the other hand, the table axis of the GE15FRplus uses a direct drive motor and a high-precision encoder and is full-closed loop controlled. However, concerns about influence on deterioration and unevenness of the rotation accuracy arose and the following solutions were implemented.

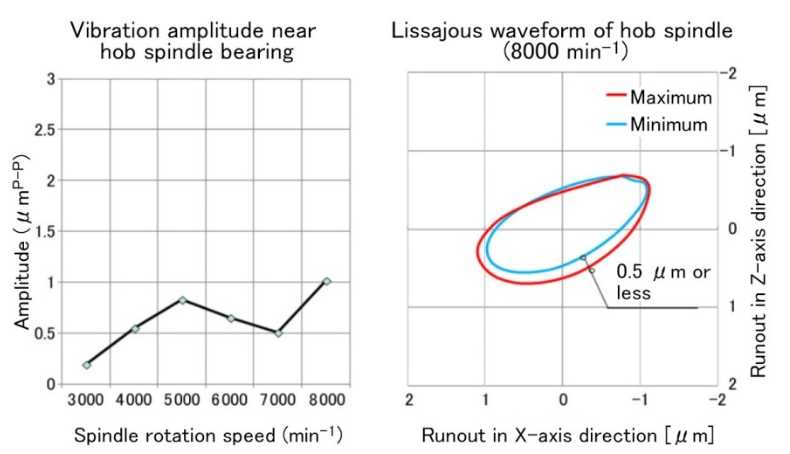


Figure 3 Vibration amplitude near hob spindle and Lissajous waveform of hob spindle

The first concern is the influence of motor cogging torque fluctuations during machining. For hobbing machines, the synchronous control of the hob spindle and the table axis is essential. In particular, the table axis rotation speed during machining a strain wave gear is low, so it is easily affected by cogging torque. Therefore, the number of motor poles and the number of slots are selected and the magnets are arranged so that the cogging torque fluctuation was minimized, and a skew type in which the rotational-direction relative phase relationship between the rotor and the stator differs depending on the axial cross section was examined and adopted.

The second concern is the influence of the contact seal sliding resistance of the table axis. When an optical encoder is used, it needs to be isolated from oil, so a contact seal may be used. In such cases, the rotation of the table axis causes an increase or fluctuation of the rotation torque due to the sliding resistance, resulting in the rotation accuracy of the table axis being affected. Therefore, in order to reduce the sliding resistance, a structure that allows oil to be isolated even with a non-contact seal is adopted to stabilize the rotation accuracy of the table axis. **Figure 4** compares the table axis rotation torques.

The table axis non-repetitive runout (NRRO) of 0.3 μm is achieved. **Figure 5** depicts the Lissajous waveform of the table axis.

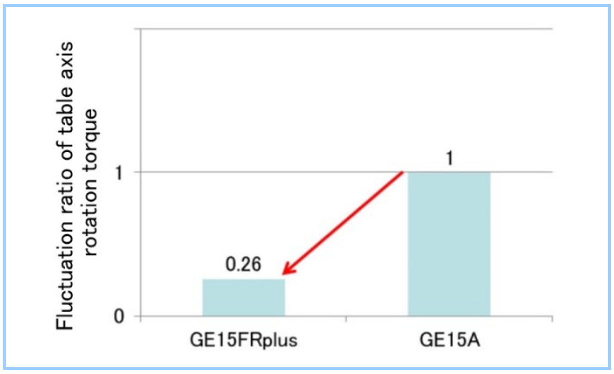


Figure 4 Comparison of table axis rotation torques

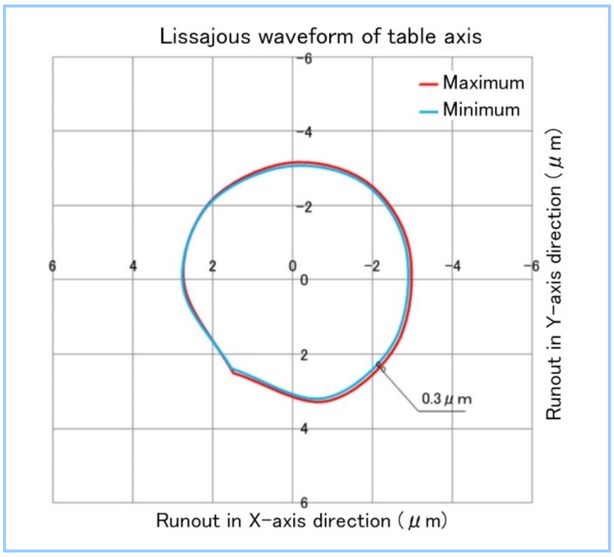


Figure 5 Lissajous waveform of table axis

4. Machining example of strain wave gear with high-precision hobbing machine

Using a carbide hob cutter, high-speed and high-feed machining of a strain wave gear with a module of 0.5, 100 teeth, a helix angle of 0° and a tooth width of 15 mm was performed at a cutting speed of 800 m/min and an axial feed of 0.5 mm. The obtained machining results are as follows.

(1) The pitch accuracy target was ISO class 3, but ISO class 1 (single pitch accuracy 0.4 μm, cumulative pitch accuracy 2.0 μm) was achieved. The single pitch accuracy and cumulative pitch accuracy were at the same level as those of gear grinding, so hobbing of a

higher-precision strain wave gear was attained. **Figure 6** gives the results of pitch accuracy machining with the GE15FRplus.

(2) The cycle time was shortened to about 1/3 of that with the GE15A hobbing machine. **Figure 7** compares the cycle times.

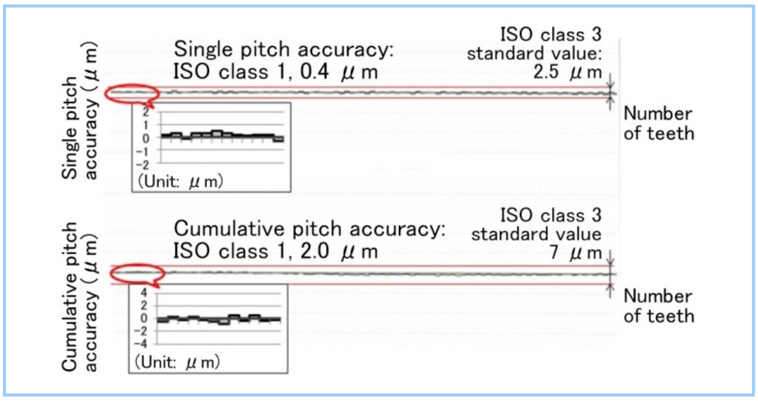


Figure 6 Results of pitch accuracy machining with GE15FRplus

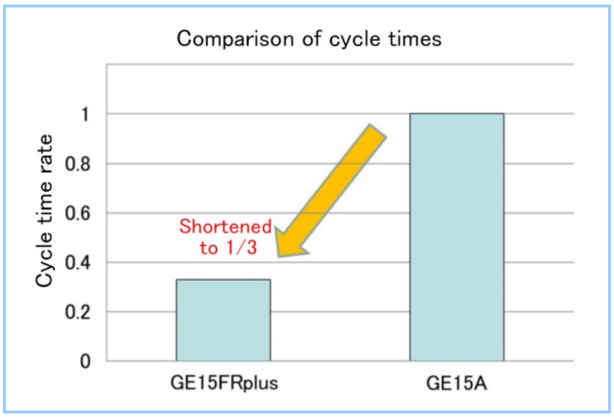


Figure 7 Comparison of cycle times

5. Conclusion

We developed the GE15FRplus high-precision gear hobbing machine for machining small-module gears using precision reduction gears in order to meet the demand for higher-precision and higher-efficiency production of such gears, which are a key component of robot articulation drives. As a result, a strain wave gear, which is a small-module gear for precision reduction gears , achieved ISO class 1 pitch accuracy, and the actual machining time was shortened to 1/3 of that of the GE15A. Based on these results, we will provide optimal gear machining solutions to major domestic and overseas users in the robot reduction gears field.