High-Speed High-Rigidity 5-Face Milling Machine MVR-D$_X$

HIROYUKI YAMAMURA*1 MUTSUMI YOSHIKAWA*1
TAKAYUKI KUME*1 HIROYUKI TAUCHI*1
YOSHIFUMI TANIGAWA*1

In recent years, in the field of large part machining, there has been an increasing need for versatile machines on which the user can use both high-feedrate tools and small-diameter drills and taps in machining, in addition to those designed for more efficient machining and those with even higher heavy cutting capabilities. To address this need with a portal 5-face milling machine, machine manufacturers must satisfy conflicting requirements: to provide the machine with a robust structure and a high-rigidity, high-torque spindle that enable heavy cutting and, at the same time, the high-speed performance to support high-feedrate tools and the capability to rotate the spindle at high speeds appropriate for small-diameter tools. To meet this challenge we utilized proprietary analysis technologies and developed and released the MVR-D$_X$, which offers more machining capabilities than conventional machines provide.

1. Introduction

Backed by the recent increase in demand by countries, especially the BRICs, power system, industrial machine, construction machine, and other heavy industries are enhancing their facilities to boost the potential need for high-efficiency machinery.

To meet this need, machine manufacturers must develop machines applicable to heavy and deep cutting as with conventional machines, yet allowing the use of a high-feedrate cutter in heavy cutting, and providing high spindle speeds appropriate for small-diameter tools.

Obviously, it is also essential to further improve the rapid traverse rate in order to reduce the non-cutting time.

To realize this, technologies that satisfy the following three requirements must be developed:

- High rigidity and light weight structure.
- Spindle with high rigidity even in the low-speed range, yet also runs at higher speeds.
- Feed system with high thrust that supports high-speed feeds.

The following describes the development of the MVR-D$_X$, focused on the technical approach to meet these requirements.

2. Machine construction

As shown in **Fig. 1**, the table moves inside the portal structure in a longitudinal direction (X-axis).

The portal structure consists of the column bridge and the crossrail and, in front of the crossrail, the ram saddle with the spindle is located. The vertical movement of the spindle is generated by the vertical movement of the entire crossrail (W-axis) and the vertical movement of the ram (Z-axis) that runs through the saddle, while the horizontal movement of the spindle (Y-axis) is generated by the saddle that moves in front of the crossrail in a horizontal direction.

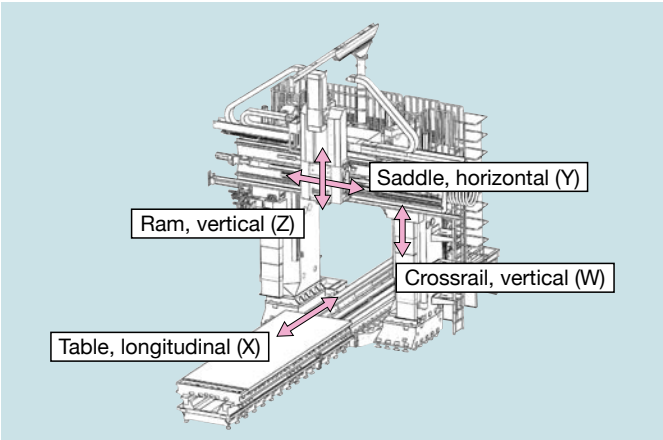

Fig. 1 Machine construction

A workpiece is loaded on the table that moves along the X-axis.

Each axis is driven accurately by the combination of a ball-screw mechanism and a linear scale. The spindle is rotated via the gear box located in the upper portion of the ram to cut the workpiece loaded on the table.

3. Machine specifications

In determining the specifications of the MVR-D$_X$, we adopted a modular design approach. We established specifications that satisfy all customer needs and divided them into standard, optional, and customer-specific categories to modularize and standardize components.

*1 Machine Tool Division

Table 1 Major specifications

			MVR28/34Dx	MVR33/39Dx	MVR38/44Dx	MVR43/49Dx
Table working surface (mm)		Width	2000	2500	3000	3500
		Length	≥4000		≥5000	
Travel of each axis (mm)						
Table longitudinal		X-axis	Table length + 1000			
Saddle, horizontal Effective travel		Y-axis	4300 3400	4800 3900	5300 4400	6000 4900
Ram, vertical		Z-axis	Standard 1000/Optional 1200			
Crossrail, vertical		W-axis	1200–3200 (Dependent on column height)			2200–3200 (Dependent on column height)
Spindle specifications						
Spindle rotational speed		(min^{-1})	7–4000			
Spindle motor output		(kW)	37 (continuous) /45 (30-minute rating)			
Feed rate of each axis (mm/min)						
Table longitudinal	Rapid traverse	X-axis	≤24000		≤20000	
Saddle, horizontal	Rapid traverse	Y-axis	30000			
Ram, vertical	Rapid traverse	Z-axis	15000			
Crossrail, vertical	Rapid traverse	W-axis	Standard 3000/Optional 5000		5000	
Maximum cutting feed			X·Y·Z 10000W 3000·5000			
Number of tools in ATC Maximum tool length Maximum tool mass		(mm) (kg)	≥60 Standard 500/Optional 800 30			
ATT (Attachment) Supported ATT			Standard: Dummy plate Right angle head (30 kW), universal head, and various other optional attachments are available			
NC system			FANUC 31i			

We also tried to offer the machine in various sizes to meet diverse customer needs (table width from 2,000 to 3,500 mm, table length from 4,000 to over 10,000 mm, loading capacity up to 100 tons, and column height from 2,050 to 4,050), as well as to reduce the delivery time. **Table 1** shows the major specifications of the MVR-D$_x$.

4. Technologies for achieving high rigidity

4.1 Selection of optimal structural materials

A machine requires robust structures with high rigidity to exhibit high cutting performance. Although "rigidity" in this sense normally represents static rigidity, the high rigidity required for a machine also includes the resistance to vibration, which is high dynamic rigidity.

To design a vibration-resistant structure, the three factors that govern vibration, "spring constant," "damping coefficient," and "mass," must be well-balanced. Although conventional machines use welded structures made of steel with a high elastic coefficient, through the use of FEM analysis, it has become possible to minimize the increase in the mass and provide static rigidity equivalent to that of a welded structure even with a cast structure.

For structures such as the ram, saddle, and table, we used cast materials as before and made them as light as possible while maintaining their rigidity to support higher spindle speeds. However, for the crossrail, columns, and bridge bed, we changed from conventional welded structures to cast materials and utilized all our analysis technologies to improve the dynamic rigidity.

4.2 Determination of target static and dynamic rigidity values

The relationship between a machine's cutting capacity and the static and dynamic rigidity values is still unsolved.

Therefore, we collected the cutting capacity and static/dynamic rigidity data from the various types of machines we had ever manufactured and organized their relationships into a database so that the target static and dynamic rigidity can be determined based on the target cutting capacity.

The target static and dynamic rigidity values for the MVR-D$_x$ were determined based on this know-how.

4.3 Process for determining structure shapes that realize high rigidity

Conventionally, the shape of each machine structure had been first determined by seasoned engineers who are familiar with where machine weak points are located based on their experience and hunches, and then verified through FEM analysis that it has the target rigidity. However, using this method, it had often been impossible to attain the target rigidity in a single attempt, which prolonged the determination of structure shapes.

We considered that this is due to the difficulty in simultaneously taking into account many conditions that determine the rigidity and, as a solution, adopted the method of determining the basic machine dimensions based on

quality engineering.

The use of quality engineering enabled us to cover all dimensional patterns that can be designed, minimize the rigidity variation caused by changes in the cutting direction or position, and derive the basic dimensions that provide light-weight structures with high rigidity.

Next, based on these basic dimensions, we prepared models of each structure and conducted FEM analysis on all structural members. We increased the wall thickness, added ribs, or used other reinforcing measures for members subjected to high stress and decreased the wall thickness, bore cast holes, and other weight-saving measures for members subjected to low stress. Implementing this process for all the structures enabled us to minimize the increase in the mass and derive shapes that provide high rigidity.

Finally, we combined the determined structures, analyzed the entire machine to check each portion was connected appropriately, and fine-tuned each structure to the target specifications to accomplish the final shapes. Using this method, although the main structures were changed from a sheet metal construction to a casting, which has a disadvantage in rigidity, we could minimize the increase in the mass and achieve the static and dynamic rigidity equivalent to or exceeding that of conventional machines.

4.4 Rigidity of MVR-D$_X$

Figure 2 shows a comparison of the actual dynamic rigidity with the value from FEM analysis.

The graph shows that both the actual and analysis values attained the target dynamic rigidity, with the frequency and the peak height at the proper value matched to a satisfactory degree.

In the analysis of dynamic rigidity, because it is essential to consider various boundary conditions, estimating the dynamic rigidity with high accuracy has been difficult. However, the accumulation of a substantial amount of know-how enabled us to improve the calculation accuracy and, as a result, analyze dynamic rigidity with excellent accuracy in the calculation stage. The synergistic effects of this high calculation accuracy and the engineering process that realized high rigidity have made the MVR-D$_X$ a machine with an excellent rigidity balance.

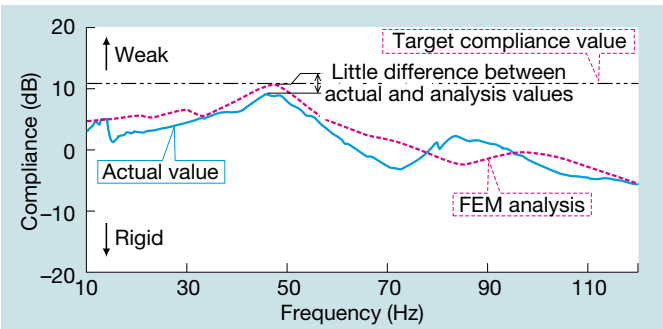

Fig. 2 Comparison of actual dynamic rigidity of MVR-D$_X$ with calculated value
Accurate estimation is possible with excellent calculation accuracy.

5. Technologies for achieving high spindle speeds

5.1 Improvements for higher spindle speeds

A machine used for heavy cutting applications requires a high-rigidity spindle that withstands large cutting loads generated during machining. Although setting a large preload on bearings improves the rigidity of a spindle, this is not a straightforward way to achieve high spindle speeds because setting an excessive preload substantially increases the heat generated from the bearings.

Although, to solve this problem, it is necessary to conduct an accurate thermal analysis and consider introducing a better cooling method, usually, doing so is not easy because of the difficulty in accurately estimating the heat generated from bearings, the coefficient of heat transfer between parts, etc. However, with the know-how of accurate thermal analysis developed through experience in various products, as shown in **Fig. 3**, we minimized the temperature rise in bearings by efficiently cooling the bearings and also reduced the temperature rise in the ram body, which is a major cause of thermal displacement. Using this technique, we successfully developed a high-precision and high-efficiency spindle capable of cutting at any speed in the range of 7 to 4,000 min^{-1}.

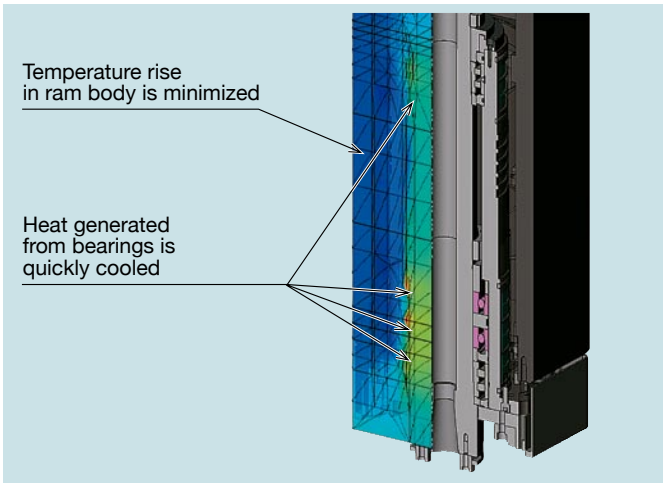

Fig. 3 Result of thermal analysis of spindle

5.2 Increasing Y-axis rapid traverse rate

For the Y-axis guide, the MVR-D$_X$ uses a roller type linear guide with high rigidity, which is suitable for high feedrates and can suppress yawing of the ram and saddle when the Y-axis is traveling. In addition, the capacity of the Y-axis feed motor was expanded to further improve the conventional Y-axis rapid traverse rate (24 m/min, which is already fast) to 30 m/min while maintaining the feed thrust.

This contributes to the reduction of the non-cutting time without impairing the advantages of high-rigidity and high-accuracy.

5.3 Z-axis feed using a twin feed motor/ball-screw system

We redesigned the Z-axis to use a twin feed motor/ball-screw system by eliminating the hydraulic-cylinder based ram balancing system, although the rapid traverse rate of the Z-axis is kept at 15 m/min, unchanged from the previous model. In addition to doing this to improve the axis rigidity during travel, we also paid attention to the layout of the ball screws so that the axis is driven at the center of gravity. This theoretically eliminates the moment caused by the unevenness of the force generated by the balancing system with that generated by the drive system, which contributes to the development of a high-precision drive. Moreover, the elimination of the balancing system contributes to the reduction of power consumption because it allows the use of a smaller hydraulic unit, which is one of the heaviest consumers of electricity in a machine tool.

6. Machining example

Backed by the high-rigidity construction obtained using the technologies as described above, the MVR-D$_x$ has a deep cutting capacity of 1,250 cc/min with a ϕ250 cutter, which is larger than that of conventional models (ϕ200), and with a helical end mill, it achieves a performance improvement from 560 cc/min to 1,050 cc/min, almost twice as large as that of conventional models (**Fig. 4** and **Fig. 5**)

In addition, in machining applications using a high-feedrate cutter, which is becoming popular, the MVR-D$_x$ achieves a cutting capacity of 2,000 cc/min or more with the right angle head, which proves the high rigidity of this machine (**Fig. 6**).

(Cutting conditions)
Tool diameter: ϕ250 mm
Cutting width: 200 mm
Infeed: 10 mm
Feedrate: 625 mm/min
Cutting speed: 200 m/min
Cutting capacity: 1250 cc/min
Workpiece material: SS400

Fig. 4 Milling
Milling application using spindle and its cutting conditions.

(Cutting conditions)
Tool diameter: ϕ63 mm
Cutting width: 31 mm (Radial)
Infeed: 60 mm (Axial)
Feedrate: 565 mm/mni
Cutting speed: 90 m/min
Cutting capacity: 1050 cc/min
Workpiece material: SS400

Fig. 5 End Milling
End-milling application using spindle and its cutting conditions.

(Cutting conditions)
Tool diameter: ϕ250 mm
Cutting width: 190 mm
Infeed: 1.5 mm
Feedrate: 7200 mm/min
Cutting speed: 220 m/min
Cutting capacity: 2052 cc/min
Workpiece material: FC250

Fig. 6 Milling using right angle head
Milling application using a high-feedrate cutter with right angle head and its cutting conditions.

7. Conclusion

The MVR-D$_x$ uses a modular design approach to support a wide range of machine specifications. By combining our abundant analysis know-how and technologies, it satisfies both high-speed and high-rigidity requirements to support more diverse machining applications than ever.

We will continue to offer cost-effective machines that meet wide-ranging customer needs by utilizing our know-how and technologies acquired through the development of the MVR-D$_x$.


Hiroyuki Yamamura


Mutsumi Yoshikawa


Takayuki Kume


Hiroyuki Tauchi


Yoshifumi Tanigawa