Development of the *SANMOTION R1* Series Small-Capacity 40, 60, and 80 mm sq. Low Inertia AC Servo Motors

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1. Introduction

Since SANYO DENKI's compact, high torque, high efficiency medium inertia R2-Series was released in 2006, it has contributed to creating value for our customers' devices and built a reputation as a long-running solution around the world by demonstrating its high standard of performance.(1) To date, we have released various models, including small-capacity R2 motors ranging in size from 40 to 80 mm sq., as well as medium and large-capacity models, ranging from 86 to 275 mm sq.(2) These products are being used for FA and a wide variety of other applications. However, with the globalization of markets in recent years, needs are becoming increasingly diversified. In order to offer our customers the optimal product for their equipment and application, there is a pressing need to offer a more diverse series lineup.(3) (4) In particular, in industrial equipment where high-hit rate operation is paramount, there is an increasing demand for servo motors with small motor inertia in order to shorten cycle time.

Acknowledging this trend, we newly developed the *SANMOTION R1* series small-capacity low inertia AC servo motor (flange size: 40 to 80 mm sq.) for applications requiring high-acceleration/deceleration drive and high response. This new product exhibits high acceleration performance in applications with low load inertia, which gives customers the optimal solution bundled together with our current models. This article focuses on the following three topics.

(1) Significance of low inertia motors
(2) Technical points of low inertia motor development
(3) Advantages of low inertia motors

2. Significance of Low Inertia Motors

If a servo motor is described as being "*low* inertia," it merely identifies its relative position compared to other models in a series, and there is no clear quantitative definition as to what constitutes as "*low* inertia."

As such, when determining the various figures concerning a motor's moment of inertia at the outset, one should consider the fundamental significance of such a motor in order to discuss what is best-suited to our customers. Here, let's consider the significance of the moment of inertia from three angles.

(1) Improved peak angular acceleration under load

Figure 1 provides a simple model of a two-inertia system. The load is connected to the motor's output shaft via a coupling. The angular acceleration, α, of the motor connected to a load is derived with the following formula:

$$\alpha = \frac{T_m}{J_m + J_L} \quad [\mathrm{rad/s^2}] \qquad (1)$$

where T_m is torque [N m], J_m is motor inertia [kg m^2], and J_L is load inertia [kg m^2].

To be deemed low inertia, the motor inertia must not only be low, but the torque must also meet acceleration requirements while under load.

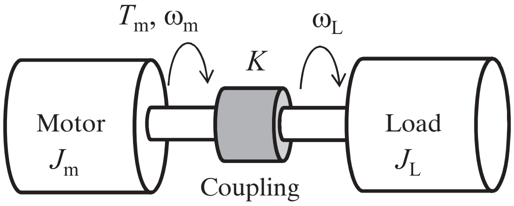


Fig. 1 Simple model of a two-inertia system

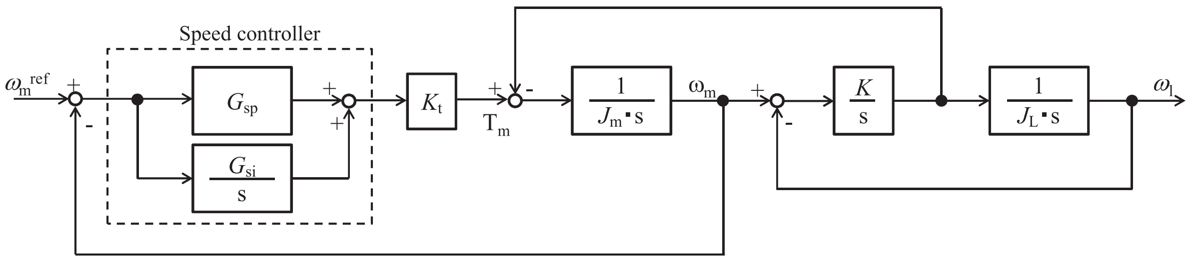
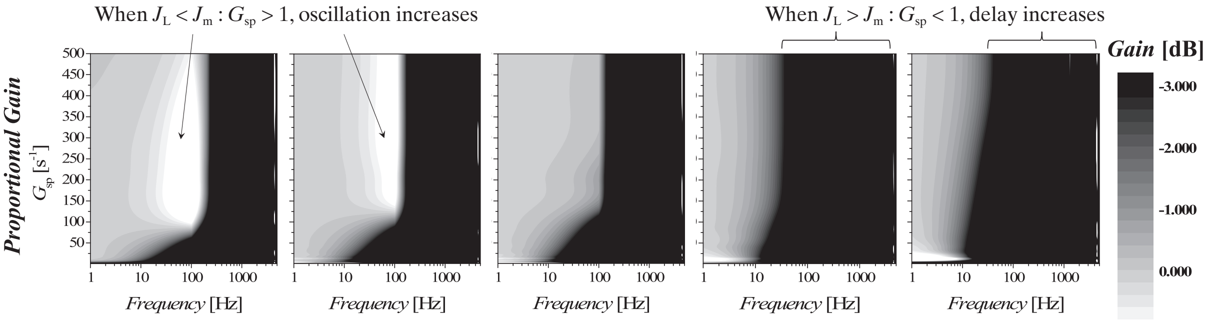


Fig. 2 Two-inertia system speed feedback control with a speed controller



(a) J_L : 0% **(b) J_L : 50%** **(c) J_L : 100%** **(d) J_L : 400%** **(e) J_L : 1200%**

Fig. 3 Effect of different load inertia ratios on the frequency response characteristic of the speed loop

(2) Improved stability of servo systems

Figure 2 shows a block diagram of a two-inertia system speed feedback control with a speed controller.(5) This figure expresses the relationship between the speed of the motor shaft, ω_m, in relation to the velocity command, ω_m^{ref}, and the speed of the load, ω_L , shown in the simple model of Figure 1.

In this figure, a sine wave with the frequency f was entered into ω_m^{ref} as the command value and used to measure the frequency response of the output ω_m. Based on this, using f and proportional gain G_{sp} as independent variables, and the amplitude gain is expressed as contours in Figure 3. This figure expresses a Bode plot in contour display. Gray indicates zero gain, the whiter levels indicate positive gain, and the darker levels indicate negative gain. Either positive or negative changes means that control is not stable.

Here, in Figure 1, if the load inertia is varied relative to the motor inertia, changes will occur in the stable, gray areas, as shown in Figure 3. J_L is defined as 100% when J_L equals J_m. For loads where J_L increases (Fig. 3 (d) and (e)), the darker area, which means the gain is lower than 0 dB, will spread. In contrast, if J_L is less than 100%, that is, the load inertia is lower than the motor inertia (Fig. 3 (a) and (b)), the positive gain region grows, causing the system to oscillate. By increasing proportional gain, G_{sp}, the stable region can be improved; however, in fact, oscillation will occur if a certain value is exceeded. Regarding this loss of control system stability due to the load inertia ratio, stability can be improved by a compensator for loads where $J_L > J_m$.(6) However, the servo system becomes fundamentally unstable for loads where $J_L < J_m$.(7)

(3) Energy-saving

Concerning section (2), motor input energy also changes depending on the load inertia ratio. If the moment of inertia ratio is $J_L = 100\%$, the kinetic energy of the load's rotating body will be the local and absolute maximum.(8) At the same time, even if the two-inertia system includes a transfer function, there exist conditions that minimize the input energy.(9) (10)

It is clear from the preceding sections (1) through (3) that to improve servo performance the ratio of motor inertia to load inertia is important. This confirms the importance of offering a motors that have a wide range of inertia ratios and offer high acceleration for industrial equipment.

With this in mind, in the early days of developing this product, SANYO DENKI first analyzed a vast amount of servo motor sizing data gathered from customers in order to determine what was the appropriate level of moment of inertia for products by each rated output. Figure 4 shows the distribution of applications in relation to load inertia and rated output. This figure expresses the motor inertia of low inertia and medium inertia motors using a dash-dotted line and solid line, and the 20-fold value as a dotted line and dashed line. Through this figure, we can tell that many devices can be stably controlled using a medium inertia motor. However, for some devices, even if the motor's required rated output increases, it is clear that there are applications where the device's load inertia is small. Moreover, if this plot were analyzed by equipment industry, in the case of robots and machine tools, the load inertia increases in proportion to the required motor output. However, for semiconductor manufacturing equipment, conveyors, and other applications that require high acceleration and speed, the load inertia is low.

In other words, the concept of the low inertia R1-Series was to develop motors optimized for particular applications by offering more stable control of loads in areas not covered by medium inertia models, as well as improve the acceleration and responsiveness of devices.

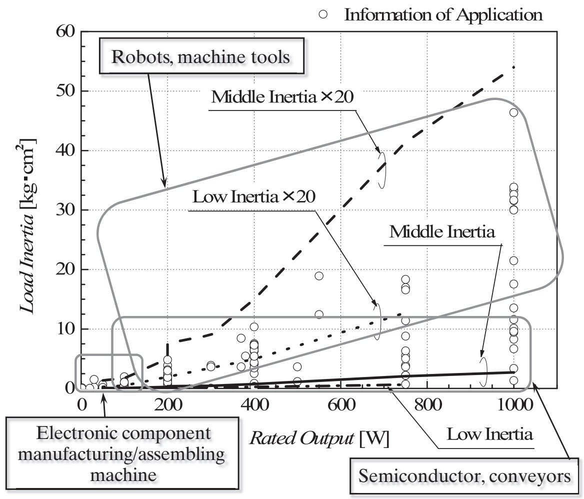


Fig. 4 Distribution of applications in relation to load inertia and rated output

3. Technical Points of Low Inertia Motor Development

Next, we will look at our approach for improving the performance of low inertia motors.

The moment of inertia around the center axis of the cylinder, J, is obtained from the following formula:

$$J = \frac{1}{32}\pi\rho l d^4 \quad [\mathrm{kg \cdot m^2}] \tag{2}$$

where ρ is density [kg/m³], l is length [m], and d is outer diameter [m].

Meanwhile, the torque generated by the motor armature, T, is determined using the following formula:(11) (12) (13)

$$T = \frac{\pi}{2} \cdot \frac{\pi}{2\sqrt{2}} \cdot k_w \cdot ac \cdot B_g \cdot D^2 l \quad [\mathrm{N \cdot m}] \tag{3}$$

where k_w is winding factor, ac is specific electric loading [A/m], B_g is specific magnetic loading [Wb/m²], D is armature internal diameter [m], and l is armature core thickness [m].

Armature inner diameter, D, and rotor outer diameter, d, are separated by a certain air-gap length. Accordingly, we can ascertain from formula (2) and formula (3) that the moment of inertia and torque are in a correlative relationship through the stator's internal diameter D; therefore, as the moment of inertia grows smaller, so too does the amount of torque generated. Of course, it is possible to increase the working area of the electromagnetic force by increasing the thickness of the armature's iron core l. However, due to a recent demand for servo motors to be compact while delivering high output, it is difficult for manufacturers to increase motor length. Therefore, to fundamentally improve torque, specific electric loading and specific magnetic loading must be increased.

To increase specific magnetic loading, the field flux source, that is, the magnetic force of the permanent magnet, must be strengthened. However, as Figure 5 shows, the growth trend for maximum energy products of rare-earth magnets has plateaued since around 2006;(14) therefore, achieving high torque by increasing field magnetic force is difficult. In light of this, SANYO DENKI decided to focus on improving torque for acceleration by increasing specific electric loading. In other words, we improved motor performance by improving the fill factor of the armature winding. SANYO DENKI has state-of-the-art winding technology specializing in high fill factor.(4) By combining production technology, our windings maximize the utility of slot areas.

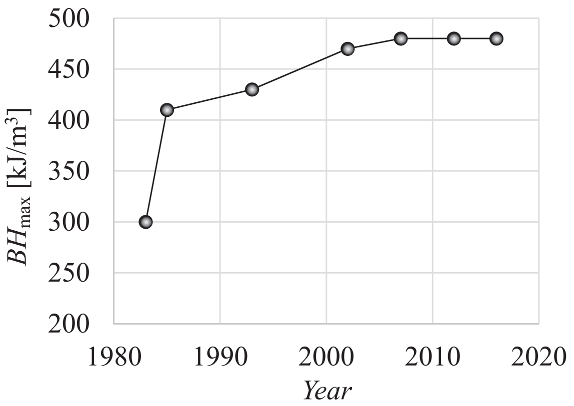


Fig. 5 Growth trend for maximum energy product of rare-earth permanent magnets

4. Advantages of Low Inertia Motors

Figure 6 shows the appearance of the newly developed R1-Series AC servo motors, while Table 1 is a list of their corresponding specifications. Figure 6 shows a typical example of the torque vs. speed characteristics. In Figure 7, the solid line shows the new model's characteristics, while the dashed line shows that of the current models. Compared with the current model, the new model has higher torque and speed, and achieves a wide output range. During high-hit rate and short stroke PTP control, triangular wave drive often begin deceleration before the motor reaches maximum speed, limiting the benefit of improving maximum speed. Meanwhile, as seen by the industry-specific plot shown in Figure 4, conveyors requiring low inertia often use trapezoid drive which moves at a constant speed when the motor is at maximum speed. By boosting maximum speed, the new models can raise device performance for this type of long stroke application.

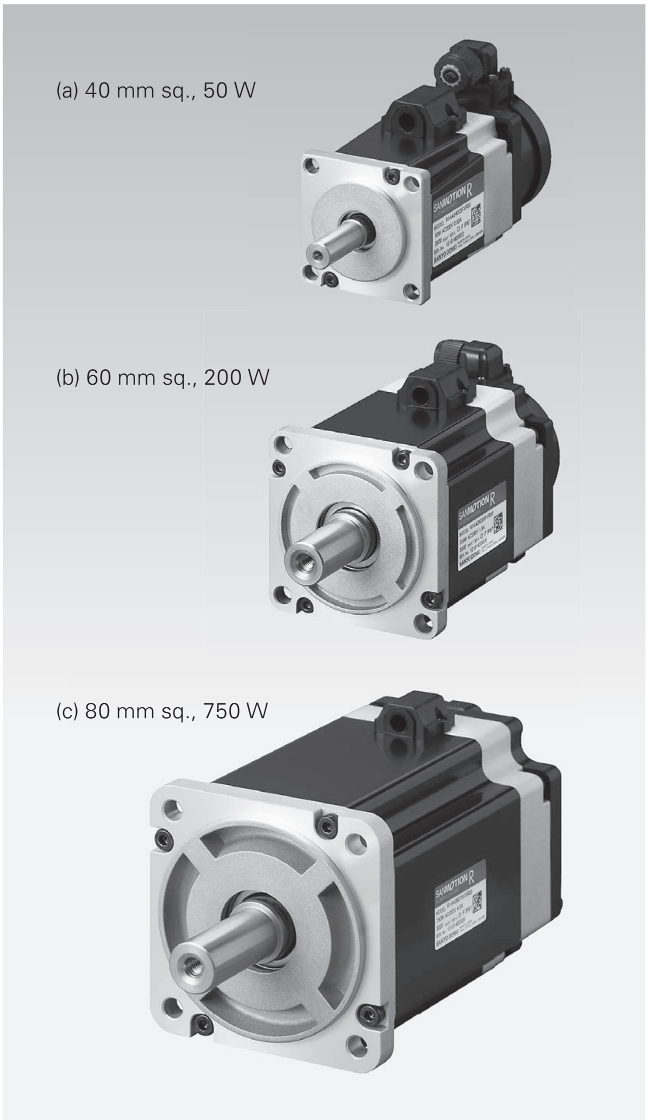


Fig. 6 Developed motors

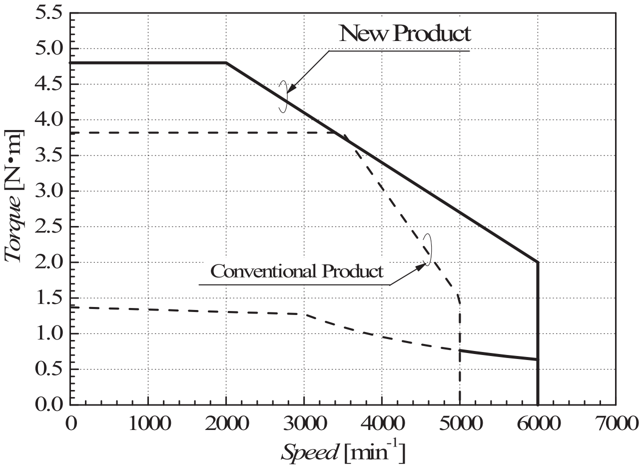


Fig. 7 Typical example of torque vs. speed characteristics
Model: 60 mm sq., 400 W, 200 VAC input

Table 1 Specifications

Items	Unit	Specifications				
Model no.	–	R1AA04005F	R1AA04010F	R1AA06020F	R1AA06040F	R1AA08075F
Flange size	mm	40 × 40		60 × 60		80 × 80
Power supply	V	200 AC				
Rated output	W	50	100	200	400	750
Rated torque	N·m	0.159	0.318	0.637	1.27	2.39
Peak stall torque	N·m	0.56	1.18	2.2	4.8	8.5
Rated speed	min^{-1}	3000	3000	3000	3000	3000
Maximum speed	min^{-1}	6000	6000	6000	6000	6000
Motor inertia	$\times 10^{-4}$ kg·m^2	0.0146	0.0242	0.122	0.203	0.719
Length	mm	84	103	96.5	121	133

4.1 Comparison of new model performance

In section 2(1), we discussed the significance of low inertia motors vis-à-vis acceleration performance. In the motor specification table, power rate and angular acceleration are indicators of acceleration performance. However, to clearly understand acceleration under load, we conducted acceleration simulation, as shown in Figure 8. In Figure 8, the motor in a static state starts rotational motion triggered by the peak torque. Then, the speed increases in line with the torque vs. speed characteristic curve, until maximum speed is reached. Here, we defined the time taken to reach the commanded speed as “response time,” and changed load inertia to calculate how response time would change.

For the simulation, we followed a simple calculation flow using motion equations only, as shown in Figure 9. We calculated the angular acceleration, α_n, and angular velocity, ω_n, and carried out calculations repeatedly until the commanded rotational angular velocity, ω_1, was reached. For torque T_n, the value of angular velocity ω_n is obtained from the torque vs. speed characteristics.

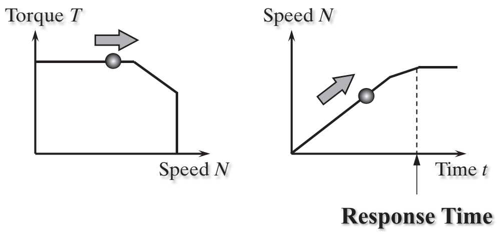


Fig. 8 Motor torque vs. speed characteristics and accelerated motion

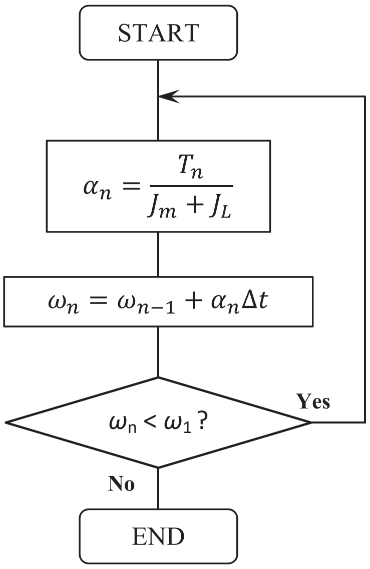


Fig. 9 Calculation flow of motor acceleration motion simulation

Figure 10 shows the relationship of load inertia and motor acceleration time. The figure also shows the response time of the 40 mm sq., 100 W motor if accelerated with a speed command of 5000 min^{-1} in the calculation flow of Figure 9. In contrast to the medium inertia R2-Series, the response speed of the current low inertia model reverses when load inertia increases. By shifting the load inertia to be as large as possible and become this cross point, the motor’s superior acceleration performance can be demonstrated across a broader area.

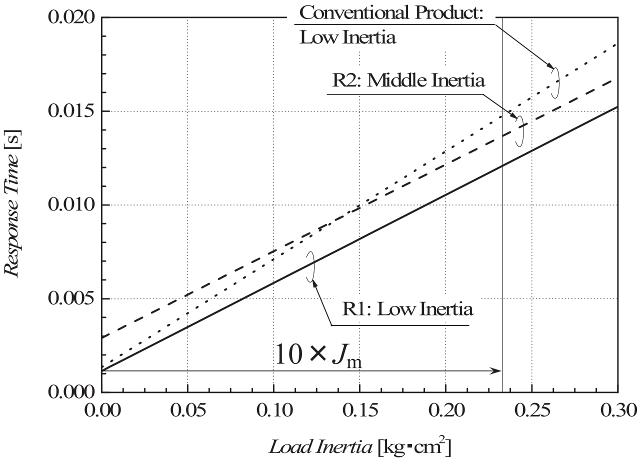


Fig. 10 Relationship between load inertia and motor acceleration time
Model: 40 mm sq., 100 W
Command speed: ω_1=523.6 rad/s (5000 min^{-1})

The new R1-Series can respond faster than the current R2-Series even with a load inertia more than 10 times the motor inertia. In this way, by exhibiting performance which sets it apart from medium inertia motors, the advantageous features of low inertia motors are more apparent.

4.2 Positioning of low inertia motor within the R-Series

In this development, by adding the small-capacity low inertia R1-Series to our current R-Series lineup, we can propose the optimal motor to suit the customer’s application. For example, when we consider the device layout image shown in Figure 11, it is necessary to incorporate various elements such as acceleration/deceleration performance in relation to the XYZ axes respectively, contouring control performance, stabilization performance, cycle-time, occupied space, and mass. In addition to this, however, it is natural that each application has its own general requirements, original customer preferences, and requirements depending on the axis even within the same device. The general-purpose medium inertia R2-Series covers a broad area in terms of wide-ranging elements; however, if the motor is tuned to perform at the limit of the device's capability, in many cases, the axis which only received a pass mark during servo tuning then becomes a bottleneck, impacting the device's overall performance. As such, it is possible to significantly improve several motion characteristics and the cycle time of the device on the whole by using products best suited for the application in relation to elements which may constrain performance. To balance the movement of multiple axes, a possible scenario may be as shown in Table 2, whereby the R5-Series(3) is used for those axes which require precision control, the compact R2-Series(4) is used if the emphasis is on weight reduction and a smaller footprint, and the new R1-Series is used for high acceleration and high response applications.

If we envision a lineup configuration map, we believe that the servo motor product lineup could be expressed three-dimensionally as shown in Figure 12. Relative to the compact, high torque, high efficiency general-purpose R2-Series model, which covers a broad area, the R5-Series, which specializes in low-speed precision feeding and positioning, and the R1-Series, which primarily offers high response and high acceleration/deceleration, are positioned as shown in this figure. Unlike a one-dimensional lineup, which was the standard for moment of inertia to date, we believe the new product lineup map is best viewed with

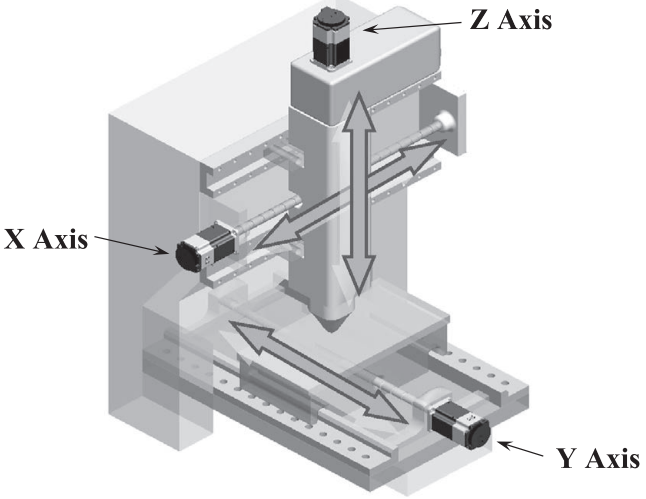


Fig. 11 Equipment configuration

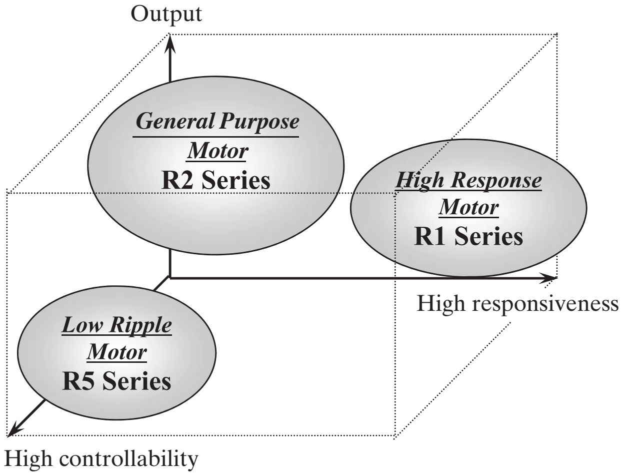


Fig. 12 3D conceptual image of the R-Series motor lineup

Table 2 Example of motor application for each shaft

Axis	General-purpose equipment	Precision control	High-speed drive	
X	R2-Series	**R5-Series** Low-speed precision feeding/positioning of the feed axis 〈Example applications〉 For applications seeking precision movement where using large motors (with a large motor inertia) and linear motors is difficult due to device layout, size, and/or cost. Etc.	**R1-Series** 〈Example applications〉 Applications where the speeds of the moving X- and Y-axes themselves become bottlenecks to the device's overall cycle-time. Etc.	
Y				
Z		—	**Compact R2-Series** 〈Example applications〉 (1) Applications where the mass of the moving Z axis itself become a bottleneck to the device's overall cycle-time. (2) Applications where the user wants to arrange multiple axes in a narrow space to increase the occupancy of working axes. Etc.	**R1-Series** 〈Example applications〉 Applications where the speed of the Z-axis itself become a bottleneck to the device's overall cycle-time. Etc.

each multifaceted dimension claiming a unique concept. By establishing a new value standard in this way, we believe we can constantly renew the significance of SANMOTION in the market to continue creating value using both our new and current models.

5. Conclusion

This article has covered the technical accomplishments of the new *SANMOTION R1* Series small-capacity 40, 60, and 80 mm sq. low inertia AC servo motor.

This motor offers both small motor inertia and improved peak torque. This drastically reduces the time required to accelerate/decelerate machines under load.

Furthermore, by promoting the new product as the perfect solution for applications requiring high acceleration and high response, together with the current models of the R2-Series and R5-Series, SANYO DENKI is now able to propose the best product for each individual shaft to suit the drive characteristics of the customers' equipment.

We hope that, with this new product, we can contribute to the creation of new value in the development of next-generation products by our customers.

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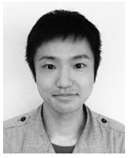

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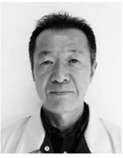

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