

Development of 2 kW Class Electric Power Unit eGX

Fumiyoshi KANBARA¹Shunsuke SAWASAKI¹Yoshihiko YAMAGISHI¹Naoki MATSUNAGA¹

ABSTRACT

The general-purpose GX series engines are installed in a broad range of work machines, serving as power sources for small construction machinery such as tamping rammers and plate compactors. Now, Honda has developed the eGX, a 2-kW-class zero-emission (zero emissions of HC/NO_x air pollutants and CO₂ greenhouse gas) electric power unit that can replace these engines. The eGX comes in integrated types and separated types, configured for differing work machine mounting conditions and usage environments. Of these, the integrated type was made for replaceability with engines of the same power band. The body size, the shape of the output shaft connected to the work machine, and other aspects are designed for replaceability with the GX engines. Since durability is important for the motor, vibration resistance of 150 m/s² or more was attained through the rotor shaft support structure and stator connecting structure. Fretting abrasion countermeasures were also implemented. In addition, a sealed motor case was used to provide the water and dust protection required on construction sites, and cooling sufficient for continuous operation at the rated output of 1.6 kW was attained with the use of inside and outside fans.

1. Introduction

Thanks to their high reliability and ease-of-mounting, general-purpose GX series engines⁽¹⁾ are used as power sources for various kinds of work machines and installed in a broad range of work machines, including those in the small construction machinery market. At the same time, in recent years the European Tier 5 Non-road Engine Emissions Regulations (otherwise known as EU Stage V)⁽²⁾ have started to go into effect, requiring even lower emissions from work machine engines. Also, for construction work inside tunnels and night-time work near residential areas, there is a demand for compact work machines and low-noise equipment. Some of this market demand has been met with work machine electrification that provides reductions in emissions and noise. However, it has become apparent that there is a need to electrify existing engine-powered work machines with minimal changes to the work machine itself while maintaining the same workability and durability.

From the point of view of workability, power supply systems for electrically driven work machines can be largely divided into power cord and battery types. Power cord-type work machines have electric motors that receive electrical power via cords plugged into an installed power source near the worksite. Power source, cord routing, and other requirements mean that such types cannot be used for all working environments and work angles/positions, and are

not suited for self-propelled work machines. With battery types, batteries may be installed inside the work machine, or attached so that they can be removed and replaced. Both methods have the advantage that, with a charged battery, they can be used at sites where there is no power supply, at unrestricted work angles/positions, and for self-propelled work machines. However, there are issues with achieving sufficient battery capacity for the required continuous run times, dealing with power shortfalls, and other challenges.

In terms of the durability of machines used in road construction and similar work, ground compaction before paving creates an environment with a lot of vibration and dust. Therefore, the motor, battery, and electrical devices need to be protected. Among existing battery-powered electrically driven work machines, there are those with exclusively designed devices and protective structures for the batteries and electrical devices. Also, output and other performance metrics are deliberately restricted compared to existing engine-powered work machines, in order to protect the electrical devices.

To respond to these needs, Honda has developed the eGX, a 2-kW-class zero-emission (zero emissions of HC/NO_x air pollutants and CO₂ greenhouse gas) electric power unit. Figure 1 shows an external view. This paper describes the technologies applied to increase the durability of the motor, which presented many technical issues in the mounting compatibility structure and inside the eGX itself.

¹ Life Creation Center

E-mail: fumiyoshi_kanbara@jp.honda



Fig. 1 External view of eGX

2. Development Goals

The development of the eGX involved two product concepts: mounting compatibility with engine-powered work machines, and performance and reliability that can withstand harsh usage environments. In concrete terms, the goals were as follows.

- (1) Packaging that would allow installation in work machines equipped with existing GX120⁽³⁾ and GX100⁽⁴⁾ engines, for compatibility with, and the same workability as, engine-powered work machines
- (2) Vibration resistance and environmental resistance to achieve durability in the expected usage environment of construction work machinery

Figure 2 shows an external view of the GX120 and Fig. 3 shows an external view of the GX100.



Fig. 2 External view of GX120



Fig. 3 External view of GX100

In addition, the following goals were set in order for the motor to have the same durability, work performance, and environmental resistance of engines.

- (a) Vibration resistance of 150 m/s²
- (b) Dust resistance (JIS Class 8 Z 8901) for levels expected to occur in ground compaction work environments at a construction site
- (c) Ability to withstand anticipated high-pressure cleaning
- (d) Cooling to allow a continuous rated output of 1.6 kW/3600 rpm or more

The above continuous rated output was a target value set to cover about 70% of work machines, based on a survey of required output for small-size construction machinery with mounted 2-kW-class engines (as of October 2021; survey by Honda).

3. Applied Technologies

3.1. Mounting Compatibility Structure

Two models of the eGX were established, according to the expected installation and running conditions of the machines in which they would be mounted. One model would be an integrated type, with the motor, battery, and power distribution unit (PDU) in a single package. The other would be a separated type, in which the control assembly, consisting of the battery and PDU, would be separate from the motor. Table 1 provides the main specifications of the eGX integrated and separated types, and the GX120 and GX100. Figure 1(a) shows the integrated type, and (b) shows the separated type. Both types would use the same removable lithium-ion battery pack and have the same workability as engine-powered work machines. Batteries would be replaceable. By having spare batteries on hand, operators could change batteries to keep the work machines operating continuously for long periods of time.

In order for the position of the motor output shaft (rotor shaft) to be compatible with installed engines, the same dimensions were used. Figure 4 shows the position dimensions of (a) the eGX and (b) the GX120.

Figure 5 shows the structure of the eGX integrated-type power unit. In consideration of the need to replace the battery during use, the battery was positioned on top of the motor⁽⁵⁾. This corresponds to the location of the fuel tank in engine-mounted work machines. To minimize the maximum width, the PDU is located on the side of the motor. Around the exterior, a plastic cover provides protection for the internal parts from external forces, dust, water, and so on. With regard to vibration resistance, the battery and PDU are composed of battery cells and a large number of electronic components. Therefore, the package included an L-shaped main frame installed to the motor and a vibration-damping mounting structure with vibration-damping rubber on the various mounting points⁽⁶⁾.

Next, Fig. 6 shows the eGX motor structure. In the motor, the stator and rotor are protected by a sealed structure consisting of aluminum front and rear cases. The stator was

Table 1 Specifications of eGX, GX120, and GX100

Model name	eGX		GX120	GX100
Type	Integrated type	Separated type	Integrated type	Separated type
Category	Permanent magnet DC motor		Single cylinder, OHV 4-stroke engine	Single cylinder, OHC 4-stroke engine
Cooling system	Forced air cooling		Forced air cooling	Forced air cooling
Shaft layout	Horizontal		Horizontal	Horizontal
Continuous rated power (kW/rpm)	1.6 / 3600		2.1 / 3600	1.7 / 3600
Maximum power (kW/rpm)	1.8 / 3600		2.6 / 3600	2.1 / 3600
Maximum torque (N·m/rpm)	5.6 / 3600 (3 s rating)		7.3 / 2500	5.7 / 3600
Set speed (rpm)	3600	3000, 3300, 3600	1400 - 3900	1850 - 4100
Noise level (L_{WA} (dB))	78	81	100	100
Overall mass (kg)	25.0	22.2	15.5	11.1
Battery mass (kg)	6.4		-	-
Operation temperature range (°C)	-15 to 40		-15 to 40	-15 to 40

fixed to the front case with bolts. The rotor has a shaft for power transmission in the center and magnets arrayed on the inner surface of the outer shell. The shaft is supported by bearings built into the rear and front cases. An inside fan is fixed to the yoke surface of the rotor, and an outside fan is fixed to the shaft. These cool the motor by creating airflow inside and outside the case, respectively. A fan cover and a top cover are positioned over the outside fan to guide the cooling airflow. These are fixed to the rear case.

For the eGX, the idea was to deploy the same parts used for generator alternators and use the same manufacturing

processes. Therefore, for the layout structure of the alternator parts, development began with the outer rotor structure, which is used in generators. In addition, the

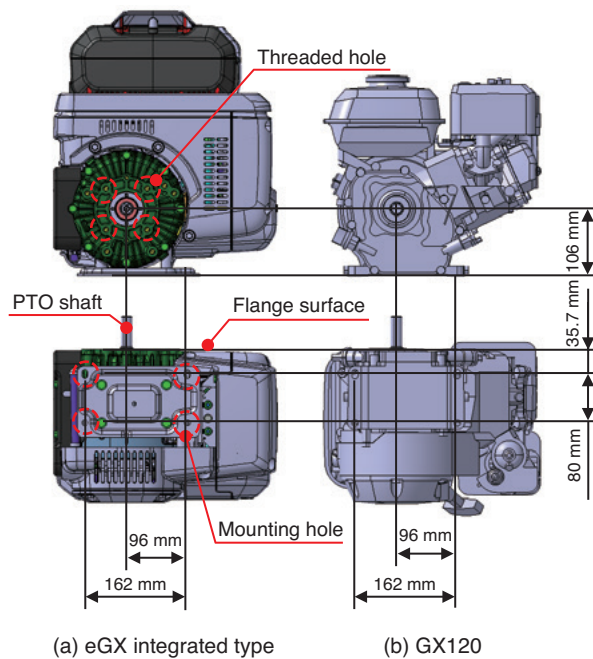


Fig. 4 Fitting dimension comparison of eGX integrated type and GX120

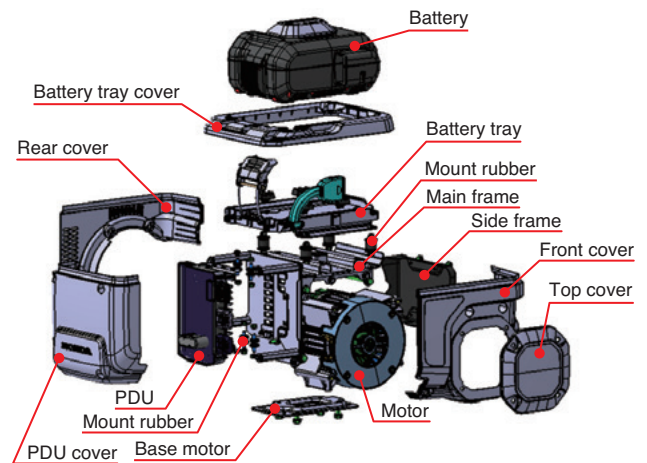


Fig. 5 Structure of eGX integrated type

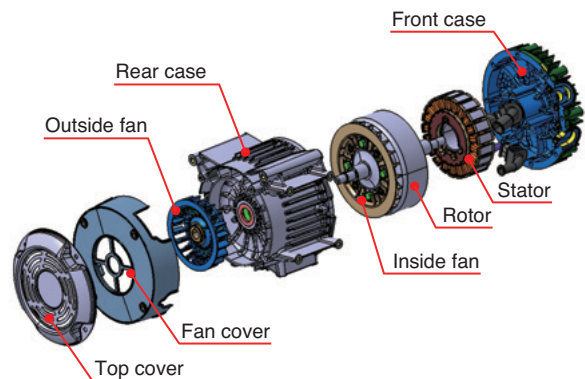


Fig. 6 Structure of eGX motor

following enhancements were made to meet the harsh environmental requirements for construction machinery, such as strength and vibration, dust, and water resistance.

3.2. Vibration Resistance

For the motor, the vibration resistance specification was set to 150 m/s² or better. This is because it was expected to be mounted on compaction machines such as tamping rammers and plate compactors, which present the harshest conditions in terms of vibration. Compaction machines tend to transmit vibration even to the power unit section, and existing general-purpose engines are also specially designed to handle strong vibrations. When assuming the mounting of an electric power unit on a compaction machine, the battery and PDU can be protected from vibrations with rubber mounts. However, the relative position of the motor's power transmission shaft and the drive unit of the machine is fixed, and rubber mounts cannot be used here. Therefore, the motor itself has to be highly vibration resistant. Accordingly, in order to create a motor with this vibration resistance, the results of assessments that determined the specifications are shown below.

3.2.1. Rotor support structure

To enhance rotor vibration resistance, the placement of the ball bearings that hold the rotor is very important. To maximize output and performance within the scope of production considerations, the air gap between the rotor and stator was set to the minimum of 0.5 mm. This air gap should be maintained even when vibrations occur in the motor section. The results of the rotor support structure assessment based on this are given here.

As described in Section 3.1., a design condition was to use the same form as generator alternators. Therefore, with the intention of using all the same yoke and magnet parts, a design was proposed in which the rotor shaft would have cantilever support that could withstand the rigors of a compaction machine, as in Fig. 7(a). At the same time, the double-sided layout that provided support with bearings on both ends of the case, which was considered to provide better vibration resistance, was also examined, although in this case there would be fewer shared parts with the generator alternator. This layout is shown in Fig. 7(b).

For the above two specifications, the rotor displacement

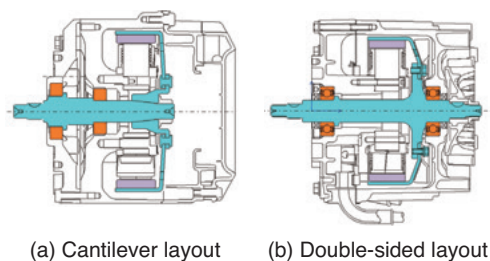


Fig. 7 Bearing layout

was calculated using a static analysis that modeled vibration excitation forces applied to the motor case in the radial direction. Figure 8 shows the results. Although the initial cantilever support structure idea met the static displacement target levels, when mounted in an actual tamping rammer, the rotor and stator came into contact. On the other hand, static analyses of the double-sided layout showed a 30% reduction of displacement compared to the cantilever support structure. This was then prototyped, and in durability tests with a tamping rammer, motor part contact was reduced. This led to the adoption of the double-sided layout.

3.2.2. Rotor shaft lubrication

The bearings were press-fitted into the front and rear cases. As the clearance between the rotor shaft and bearing was set loosely, there was concern that small vibrations could occur that would cause wear on the rotor shaft. If this wear were to progress, it would be possible that the clearance would increase, leading to increased noise, reduced motor efficiency, excessive vibration, and damage. Therefore, it would be necessary to reduce the amount of wear.

The amount of wear was assessed for tamping rammer mounting. Figure 9(a) shows an image of the rotor shaft after durability testing without additional protection. The brown areas show sections of bearing contact, and wear with pitching has occurred.

Here, an enhanced specification was considered. Figures 9(b), (c), and (d) show images of bearing contact on the shaft after applying various specifications and conducting durability tests.

Figure 9(b) shows a shaft with molybdenum disulfide coating. The molybdenum disulfide coating reduced initial wear, but as operating times increased, the amount of wear also increased. The molybdenum coating itself lacked durability, so while it provided good initial lubrication, this performance could not be maintained.

Figure 9(c) shows a shaft treated with a hard chrome plating. The aim was to reduce the amount of wear by increasing surface hardness by 17%, and the intended result was obtained.

Figure 9(d) shows the application of general-purpose industrial grease between the shaft and bearing to help

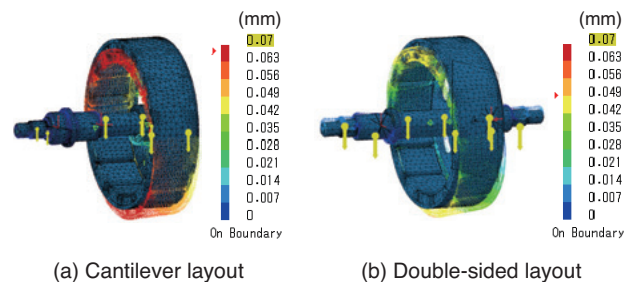


Fig. 8 Rotor displacement

avoid direct contact between metals. Durability testing resulted in a reduction of wear to less than 1/10. Also, the amount of wear was reduced, without maintenance, even when operation exceeded the expected life of the eGX.

With two good results to choose from, in the form of hard chrome plating or grease, grease application was selected for its good manufacturing and engineering characteristics.

3.2.3. Rotor shaft/yoke fastening structure

To provide the eGX with general-purpose versatility, Honda prepared the necessary range of shapes of output-shaft-type rotor shafts. By separating the yoke/magnet section and shaft sections of the rotor, the shaft only could be provided in multiple specifications. The results of assessments of the fastening structure for the separated sections are given here.

Figure 10(a) shows a structure in which, in the same way as generator alternators, a hub is placed between the yoke and shaft, and the yoke and hub are fastened together with rivets. When the motor with this specification was mounted in a tamping rammer, as shown in Fig. 11, fretting abrasion developed and advanced on the contact surfaces of the yoke and rivets. This wear could not be mitigated.

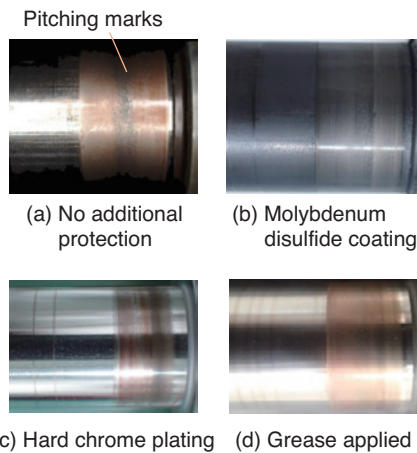


Fig. 9 Shaft condition inside of bearing after durability test

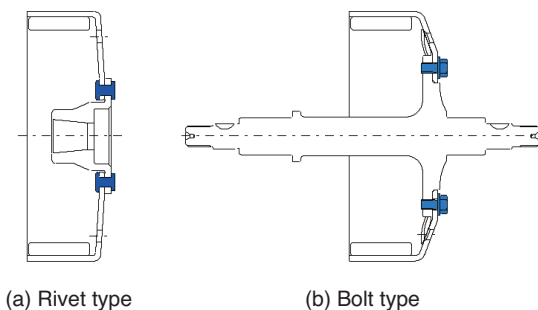


Fig. 10 Rotor shaft fastening

The rotor shaft was therefore connected to the yoke with bolts⁽⁷⁾. This is shown in Fig. 10(b). This change addressed the issue described above, and was adopted as a specification.

3.2.4. Stator fastening structure

The stator was fastened to the front case with a bolt. The fastening point was limited to a position between the slot and the shaft due to its structure, but it was necessary to suppress stator slot vibration and protect the electrical winding.

On generators, two M5 bolts were used for this fastening, but on a tamping rammer, this damaged the stator. It was believed that the cause of this was resonance of the stator. Figure 12 shows the results when acceleration of the stator was checked by applying acceleration of each frequency to the front case. When the stator was fastened with two bolts, the point of resonance was around 360 Hz. Additionally, analysis of the tamping rammer input vibration components showed that there was a main input caused by the rolling compaction cycle at around 11 Hz, but there was also a relatively large input at around 400 Hz. It was inferred that the characteristics of this input and stator resonance generated excessive vibrations that impacted the strength of the stator.

As a response, a fastening was assessed that used three M6 bolts to increase the point of resonance to 500 Hz or more. The result, as shown in Fig. 12, confirmed that the acceleration near 360 Hz was reduced to about 1/10 of the previous figure, and the resonance point became 600 Hz or higher. This change addressed the issue described above, and was adopted as a specification.

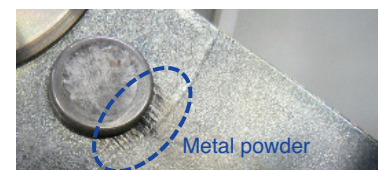


Fig. 11 Fretting abrasion on plane of rivet

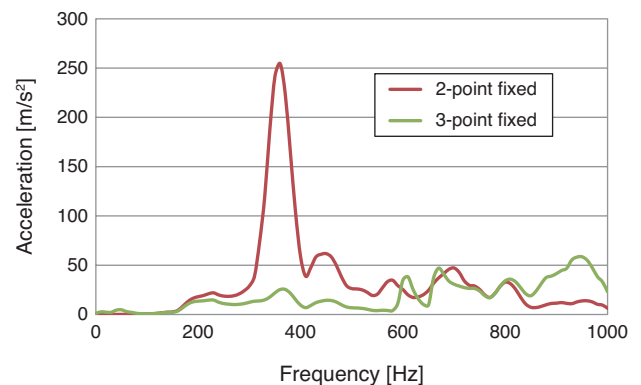


Fig. 12 Acceleration of stator

3.3. Environmental Resistance

3.3.1. Dust and water resistance

Figure 13 shows the internal structure of the eGX. As shown in Fig. 14, the motor section was protected with a dust seal to stop dust and water from entering through the shaft area. Figure 15 shows the drain holes and vent hole in the motor case. The drain holes located at the bottom of the motor section help ensure that water will be discharged in cases when water contaminates the motor due to an unanticipated event. The vent hole located higher up on the motor is part of the water protection specification, and enables the water to drain from the drain holes.

3.3.2. Cooling

When considering motor cooling, it is important to understand stator loss level, as this is a source of heat generation. Figure 16 shows a total loss analysis during eGX rated operation. The breakdown of the total loss during rated operation was about 20% for the motor controller and about 80% for the motor itself. With regard to this motor loss, copper loss that occurs in electrical winding and iron loss that occurs in the core together account for 47% of loss. Friction loss in the bearings accounts for about 23%. Airflow loss from the outside and inside fans used in this design accounts for about 12% of loss. Some of the iron loss is externally cooled by direct heat conduction from the

core to the case or shaft, but part of the iron loss and all the copper loss is discharged into the inside of the motor, and this leads to an increase in the localized temperature. This means that temperature protection provided by the internal sensor for pulse detection affects the continuous rated operating time of the power unit.

Therefore, the following cooling methods were considered.

Figure 17 shows the detailed structure of the motor.

The 21 poles of the stator core consisted of electrical winding on insulators, and each winding is connected by a bus ring. The sensor for pulse detection is fastened to the stator core, and the stator core is fastened to the case by bolts. Fourteen pole magnets are attached to the inner circumference of the rotor yoke, and these rotate through the air gap at the outer circumference of the stator. For the motor type, an outer rotor structure is used. The benefit of the outer rotor structure is that it is possible to array the magnets of the rotor on the outer circumference, thus allowing for larger magnets. In particular, for manufacturing purposes, ferrite magnets are used in the motor and in the manufacture of power generators. Compared to the more commonly used neodymium-type rare earth magnets, the maximum energy product is as low as 1/5 or less.

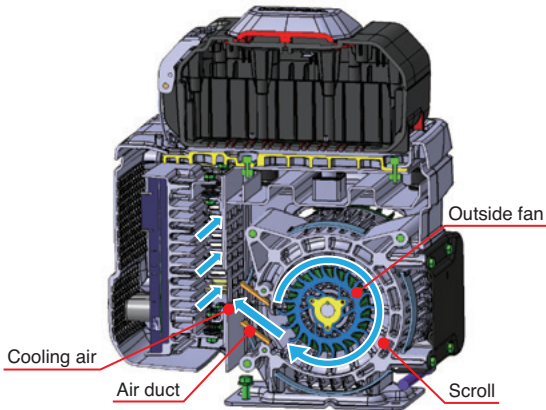


Fig. 13 Internal view of eGX

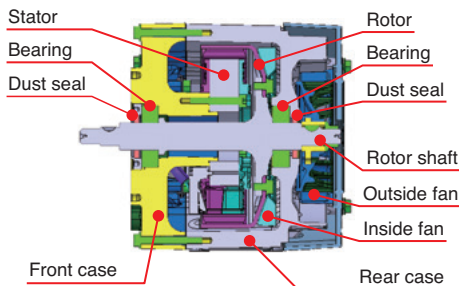


Fig. 14 Internal view of eGX motor

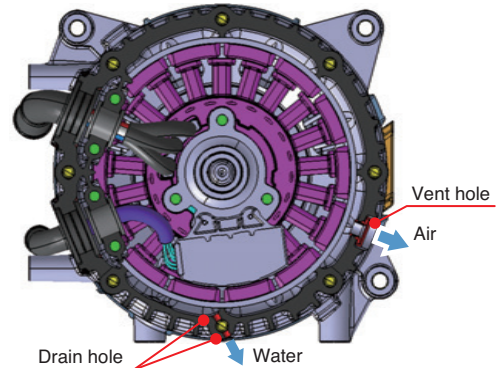


Fig. 15 Water hole layout

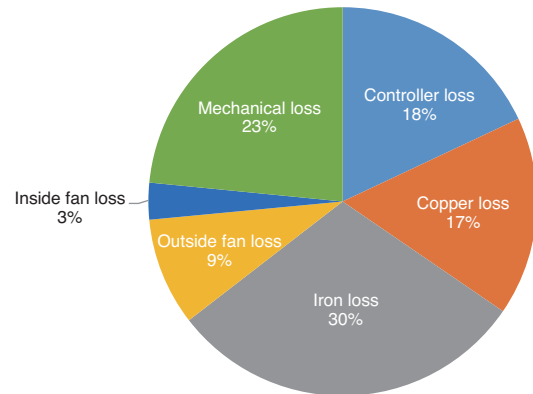


Fig. 16 Loss analysis of electric power unit

By arraying more magnets on the outer circumference and increasing the equivalent cross-sectional area of the magnets, the amount of air gap flux between the stator and the rotor could be increased.

On the other hand, the electrical winding of the stator is located on the innermost side, passing through the air gap with the rotor core as well as the air gap with the case. This presents an issue for the outer rotor structure; namely, having to cool the surrounding sections that are heated due to the current flowing through the electrical winding.

In many general-purpose industrial motors, a cooling method is used in which an outside fan is located above the shaft, and the airflow from this fan is circulated by forced convection to the outer part of the motor case. However, the eGX has an enclosed motor case for the purpose of dust and water protection when used in construction machinery. Therefore, the cooling airflow from the outside fan alone was not sufficient to reduce the internal temperature of the motor. Due to this, the installation of an inside fan was investigated as a means to create cooling airflow inside the motor. Figure 18 shows the results of fluid analysis of cooling airflow generated by an inside fan, using a simple model.

Since it was a challenge to reproduce the air gaps between 21 adjacent electrical windings in this analysis, the fluid analysis was performed using a simple model with a wider air gap between the stator and rotor.

The inside fan mounted on the upper part of the rotor rotates and pushes the air inside the stator to the outside of the fan. This air passes through the gap between the outer surface of the rotor and the inner surface of the case and flows to the lower side of the stator. At the same time, the air at the lower side of the stator flows to the rear upper surface over the electrical winding of the stator. This internal air circulates between the electrical winding, where copper loss heat generation occurs, and the stator core, where iron loss heat generation occurs, and thus carries the heat from inside the motor to the outer case.

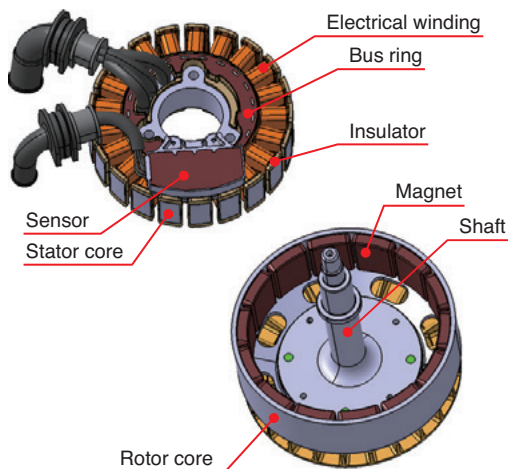


Fig. 17 Detailed structure of motor

Figure 19 shows the result of the flow rate analysis of the airflow through the gap between the outer surface of the rotor and the inner surface of the case. Based on the calculations, four times greater internal airflow can be expected in a motor with an inside fan compared to one without such a fan.

As a result of this investigation, the eGX motor was equipped with both an outside and inside fan for cooling purposes. Figure 20 shows a cross-sectional view of the cooling system. To summarize the cooling airflow,

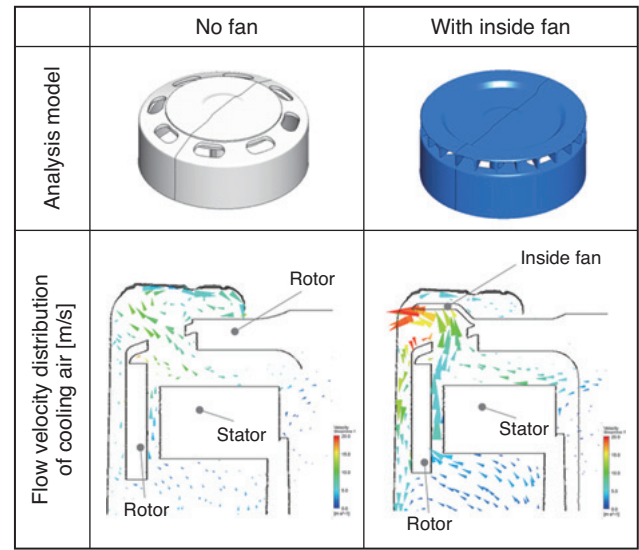


Fig. 18 Fluid analysis result inside motor

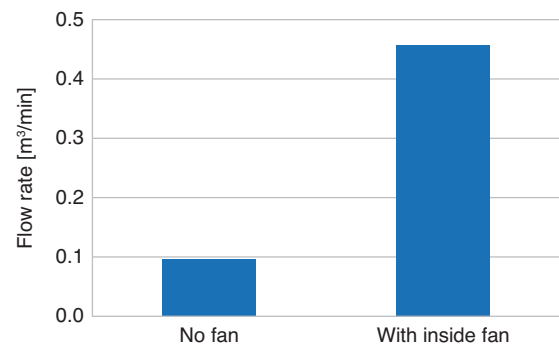


Fig. 19 Flow rate passing through gap between rotor and case

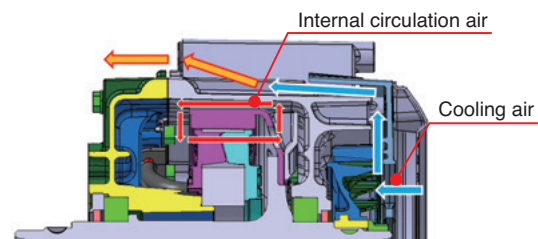


Fig. 20 Image of motor cooling system

Table 2 Temperature rising test result at rated point after 50 min

Measurement place	40°C conversion		
	No fan (°C)	With outside fan (°C)	With inside and outside fans (°C)
Motor internal atmosphere near sensor	91	74	67
Internal sensor	96	78	69
Electrical winding (Rear side)	150	130	96
Electrical winding (Front side)	141	122	91

the inside fan draws the internal air around the electrical winding from a hole to the rotor core and the air inside the motor is circulated by convection. This raises the heat transfer rate from the electrical winding to the air inside the motor and from the internal air to the housing. The outside fan dissipates heat from the housing into the atmosphere by blowing cooling air on the outer surface of the housing⁽⁸⁾.

Next, Table 2 shows the test results comparing temperature rises after 50 minutes for different conditions during rated motor operation. The test compared cooling performance under three conditions: no fans at all, outside fan only installed, and inside and outside fans installed. With no fans, the temperature of the electrical winding rose rapidly, the motor's internal temperature also rose, operating temperatures were not maintained, and continuous rated operation could not be attained.

When only the external fan was installed, the internal temperature of the motor was about 20°C lower than with no fans at all, but a localized temperature rise occurred around the electrical winding and operating temperatures were not maintained.

In a setup with both inside and outside fans, operating temperatures were maintained and continuous operation was possible.

4. Conclusion

Honda has developed the eGX, a 2-kW-class zero-emission electric power unit that is able to withstand the harsh usage environments faced by small construction machinery market. The following technologies were used to achieve mounting compatibility and motor durability.

- (1) In consideration of the work machine mounting conditions and usage environment, an integrated type and separated type were established. The integrated type was made for mounting compatibility with engines of the same power band. The packaging was constructed so that the external dimensions, layout of electrical devices, and position and installation surface of the output shaft had the same dimensions.
- (2) With regard to motor durability, by optimizing the rotor shaft support structure and implementing fretting abrasion countermeasures on the bearings support parts,

using a bolt-fastening structure between the yoke and rotor shaft, and optimizing the stator fastening, Honda built a motor that could withstand vibrations of 150 m/s² or more.

- (3) In terms of environmental resistance, mainly by using a largely sealed-structure motor case, Honda built a motor that was protected against both dust and water. Also, by using a design that had inside fans in the motor as well as outside fans, Honda achieved sufficient cooling for a continuous rated output of 1.6 kW/3600 rpm.

These have made it possible to meet the need to electrify existing engine-driven work machines in the face of ever-tightening environmental regulations.

References

- (1) Japan Land Engine Manufacturers Association: Honda GX enjin no shinka o furikaeru, LEMA, No. 530, p. 19-33, (2018) (in Japanese)
- (2) Regulation (EU) 2016/1628 of the European Parliament and of the Council, Chapter I, Article 4. Engine categories, (2016)
- (3) <https://www.honda.co.jp/engines/GX/GX120/>
- (4) <https://www.honda.co.jp/engines/GX/GX100rammer/>
- (5) Patent Publication No. WO2020/049617, (2020)
- (6) Patent Publication No. WO2020/194728, (2020)
- (7) Patent Publication No. WO2020/202390, (2020)
- (8) Patent Publication No. WO2020/202391, (2020)

■ Author ■



Fumi Yoshi KANBARA



Shunsuke SAWASAKI



Yoshihiko YAMAGISHI



Naoki MATSUNAGA