

Development of Micro Combined Heat and Power Generation Unit with Extended Expansion Linkage Engine

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ABSTRACT

A micro combined heat and power generation (CHP) unit that uses an extended expansion linkage engine (EXlink) has been developed with the aim of simultaneously enhancing fuel efficiency and reducing the unit size. This is the first mass production known to date of a compact engine that uses an original multiple linkage system to realize an Atkinson cycle.

EXlink increases the power output efficiency by using a linkage system to extend the expansion and exhaust stroke lengths relative to the intake and compression stroke lengths. Use of EXlink in a micro CHP unit increased the power generating efficiency by 3.8 points to 26.3% (lower heating value: LHV), and optimization of the heat flow design also increased the overall efficiency by 6.5 points to 92% (LHV), compared to the 2006 model.

The increased engine efficiency enabled reduction of the intake air amount which reduced the intake and exhaust noise and achieved a CHP unit noise value of 43 dB(A)/1m (Japanese specifications).

A depth of 298 mm was achieved in consideration of installation in the narrow spaces around a typical Japanese house. In addition to revision of the parts layout, this realized a 33% reduction in chassis volume and an 11-kg weight reduction compared to the 2006 model.

1. Introduction

Environmental awareness continues to increase due to global climate fluctuation and energy issues, and various efforts are being made in each sector to reduce CO₂ emissions. Energy consumption in the civil sector (households) also continues to grow steadily around the world, and has become a major factor behind the nonstop growth in overall energy consumption.

Combined heat and power generation (CHP) systems use a generator to generate electricity, while simultaneously recovering and using the heat produced by the power generation process. CHP systems are viewed as an effective means of reducing CO₂ emissions, and have been widely used for some time centering on large-scale private industrial power generating facilities that also serve as heat sources.

Honda applied its engine and inverter generator technologies developed for power products, and released a compact CHP unit for Japanese households in 2003⁽¹⁾. This was followed by the release of a second-generation model (hereafter “2006 model”) in 2006, and had achieved cumulative shipments of 110000 units as of June 2011.

Honda has now developed a third-generation micro CHP unit that provides further enhanced environmental performance in an even more compact size. This unit is the first known to date to employ an extended expansion linkage engine (hereafter “EXlink”) that uses an original multiple linkage system to realize an Atkinson cycle.

2. Development Goals

Most industrial CHP systems are mainly used to supply electrical power, and employ a “power first, heat second” operating pattern that constantly generates electrical power. The heat produced at that time is also used, and excess heat is disposed. On the other hand, households can be expected to demand not only electricity, but also a certain amount of heat in the form of hot water and heating. Therefore, Honda systems employ “heat first, power second” operation that stores heat in the form of hot water in a hot water storage tank, and operates until the hot water reaches a certain temperature and amount. Operation is controlled according to predicted high power and heat usage time periods based on learned time periods, realizing a low-waste household system.

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Figure 1 illustrates micro CHP system installation in a typical Japanese household.

Electric power generated by the CHP unit installed outdoors passes through a power distribution board and is consumed by the electric appliances in the household. Heat is stored as hot water in the hot water storage tank, and used as necessary for hot water supply, underfloor heating, bathroom heating and other heating uses. A supplementary boiler is installed in the hot water storage tank to prevent the system from running out of hot water.

Like the previous systems, the newly developed model also employs heat first, power second operation, and generates power of 1 kW while using both a hot water storage tank and supplementary boiler. Product appeal was enhanced as follows.

(1) Increased power generating efficiency

Electricity has a higher economic value compared to hot water with the same amount of energy, and is a form of energy that can be converted to various applications. CHP systems produce high-value electrical energy, and the remaining energy is also not wasted and can be used as hot water. This means that CHP systems can be said to be more economic when compared to systems such as hot water boilers that convert the energy of fuel into hot water. As a result, higher power generating efficiency is demanded of CHP systems as power generating facilities.

(2) Increased heat recovery efficiency

Micro CHP systems are both power generating facilities and hot water supply facilities, so the heat recovery efficiency is extremely important. When only the power generating efficiency is increased without changing the amount of energy discarded from a micro CHP unit, the amount of recovered heat decreases. Therefore, efforts were made to increase the heat recovery efficiency by minimizing the ventilation air flow. In addition, an oil cooler heat exchanger integrated with an oil pan was used to increase the amount of heat recovered from the engine oil.

(3) Reduced vibration and noise

Japanese specification micro CHP units are installed on residential land and are also anticipated to operate in the early morning and evening hours when there is heat demand, so a higher level of quietness is demanded compared to other products with engines. In addition, it is

assumed that the reduced size will result in installation in even narrower outdoor spaces compared to the 2006 model, so development aimed to both reduce the overall noise and enhance the sound quality.

(4) More compact size

The goal was to develop a unit with a width of 300 mm or less that could be installed in spaces as small as 650 mm, including the maintenance space, to enable installation and the necessary maintenance in narrow spaces between houses and property lines (Fig. 2). In addition, the overall height was also reviewed to facilitate installation below bay windows, with the ultimate goal of a 33% reduction in volume compared to the 2006 model.



Fig. 2 Example of 650 mm exterior space

3. Introduction of Developed Technologies

3.1. Increased Power Generating Efficiency

3.1.1. Use of EXlink

The EXlink engine was employed to increase the power generating efficiency.

EXlink adds trigonal link, swing rod and eccentric shaft linkage systems to the connecting rod and crankshaft of a normal engine, and rotates the eccentric shaft synchronized at half of the crankshaft rotations. This realizes an Atkinson cycle in which the lengths of the intake and compression strokes differ from those of the expansion and exhaust strokes (Fig. 3)⁽²⁾⁻⁽⁹⁾.

Setting shorter intake and compression stroke lengths and longer expansion and exhaust stroke lengths enables more work to be performed with less intake, which increases the thermal efficiency compared to a normal engine.

Table 1 lists the specifications of the engine (GE160V) mounted in the 2006 model and the engine (GFV110) mounted in the newly developed model (hereafter “2011 model”). The compression ratio was set to the same as the 2006 model, and the expansion ratio was set at 17.6. In addition, reducing the bore diameter enabled reduction of the combustion chamber size, and arranging the intake and exhaust valves in a radial shape around the combustion chamber with the spark plugs located closer to the center

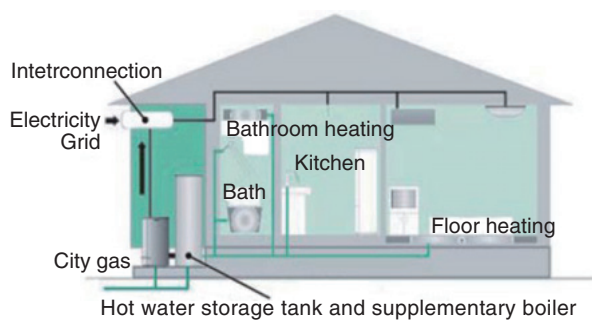


Fig. 1 Micro combined heat and power generation system

Table 1 Comparison of 2006 model and 2011 model engine specifications

	2006 model	2011 model
Engine name	GE160V	GFV110
Bore diameter (mm)	φ62	φ53
Intake/compression stroke (mm)	54.0	49.8
Expansion/exhaust stroke (mm)	54.0	74.1
Intake/compression volume (cm ³)	163	110
Expansion/exhaust volume (cm ³)	163	163
Compression ratio	12.0	12.2
Expansion ratio	12.0	17.6
Rated speed (rpm)	1,950	1,950

created a hemispherical combustion chamber with good combustion efficiency. Figure 4 shows the engine structure.

In addition to the higher expansion ratio and modified combustion chamber shape, the intake stroke volume was also optimized. This increased the engine brake thermal efficiency at rated operation by 16.4% compared to the 2006 model.

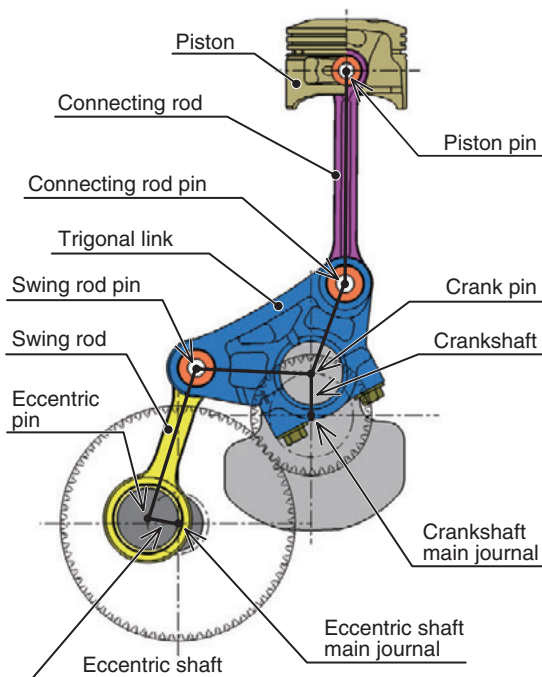


Fig. 3 Configuration of EXlink

3.1.2. Increased electrical conversion efficiency

The conversion efficiency of the alternator that converts the axial power output generated by the engine into electrical power output and the inverter unit that converts that electrical power output into interconnectable electric power was also increased in order to increase the power generating efficiency. Figure 5 shows the interconnection power generating block diagram.

3.1.3. Technologies to increase alternator efficiency

Alternator loss consists of iron loss that depends on the magnetic materials and copper loss that depends on the windings. Iron loss is divided into eddy current loss, which is the Joule heat loss when eddy current is generated by a magnetic field passing through the iron core, and hysteresis loss, which is generated according to the hysteresis curve (B-H) of the magnetic body. Equation 1 shows the typical formula for eddy current loss We , and Eq. (2) shows the typical formula for hysteresis loss Wh .

$$We = af^2 Bm^2 \quad (1)$$

$$Wh = bf Bm^{1.6} \quad (2)$$

a : Constant determined by the magnetic body plate thickness

b : Constant determined by the magnetic body material

f : Alternator frequency

Bm : Magnetic flux density

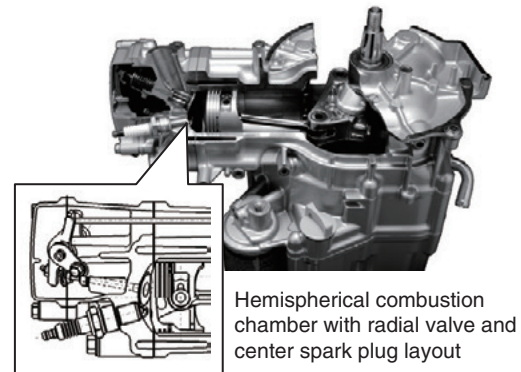


Fig. 4 External and sectional view of 2011 model engine

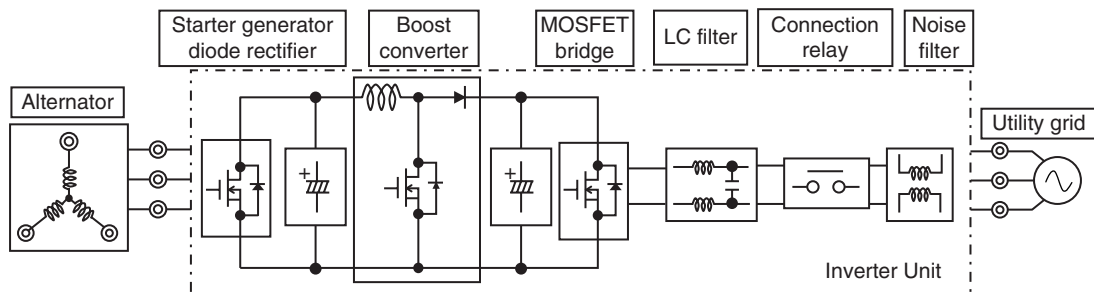


Fig. 5 Block diagram of interconnection inverter and alternator

This development focused on iron loss, and the following three technical elements were used in the 2011 model to reduce loss.

(1) Reducing iron loss by lowering the frequency

Equations (1) and (2) indicate that reducing the frequency can effectively reduce iron loss. Figure 6 shows the alternator used in the 2011 model. The frequency was lowered by reducing the number of stator slots and rotor poles. Normally this would also lower the rated voltage, but the rated voltage was kept the same as the 2006 model by increasing the core layer thickness.

(2) Reducing eddy current loss by reducing the eddy current in the core

The constant a in Eq. (1) is proportional to the square of the magnetic body plate thickness. Eddy current loss in the 2011 model was reduced by reducing the stator core plate thickness.

(3) Reducing the rate of magnetic characteristic deterioration due to blanking strain

The constant b in Eq. (2) can be reduced by eliminating factors resulting in deterioration of the magnetic characteristics of the magnetic body. In the 2011 model, the strain produced by blanking and forming was reduced by reducing the stator core plate thickness, and hysteresis loss was reduced by reducing the deterioration in magnetic characteristics.

Application of the efficiency enhancing technologies (1) to (3) above achieved an increase in the conversion efficiency of the alternator assembly.

3.1.4. Technology to increase inverter efficiency

Efficiency was increased in the 2006 model by carefully selecting the switching elements and the choke coil core materials to realize a high efficiency interconnection inverter⁽¹⁰⁾. In the 2011 model, loss was reduced by focusing on the switching frequencies in the boost converter block that boosts the DC voltage generated by the alternator and diode rectifier shown in Fig. 5 to a DC voltage that enables interconnection with the electric grid, and the MOSFET bridge block that converts the boosted DC voltage into an AC voltage in accordance with the grid voltage and frequency. The switching element circuit configuration and the LC filter constants were reviewed, and the switching frequency was reduced. This reduced both the switching

loss of the boost converter and MOSFET bridge blocks and the iron loss of the choke coil in the LC filter block, thus achieving an increase in the conversion efficiency of the inverter unit.

3.1.5. Increased power generating efficiency

By increasing the thermal efficiency of the engine and the conversion efficiency of the alternator and inverter, the power generating efficiency of the unit was increased by 3.8 points from 22.5% (lower heating value, hereafter “LHV”) for the 2006 model to 26.3% (LHV).

3.2. Increased Heat Recovery Efficiency

CHP units extract the energy possessed by fuel as electric power via an engine, alternator and inverter, and recover the heat generated by that process via cooling water using an exhaust heat exchanger and an engine cooling system. Low-temperature heat is absorbed by the ventilation air and exhaust, and exhausted to the outside of the system as disposed heat.

Ventilation cools by stealing the heat from the surface of each part such as the engine and electronic parts, and the air flow is set so that all components are cooled to the appropriate temperature or less. In order to increase the heat recovery efficiency, a reduction in the amount of the ventilation air was sought by ventilating effectively.

Increasing the conversion efficiency reduced the amount of heat generated from heat-generative elements, and enabled reducing the air flow required to cool electronic parts.

The ventilation air flow and the engine cooling system were enhanced to enable cooling of the entire unit by the reduced air flow.

3.2.1. Optimization of ventilation air flow

The locations inside the unit that require active cooling by ventilation are as follows.

- Inverter (electronics room)
- ECU (electronics room)
- Alternator (coupled to the engine)
- Engine mount (engine room)

The engine and hoses are cooled by cooling water.

In the 2006 model, a high amount of air was required because the alternator coupled with the engine was cooled using a fan mounted on the alternator by means of the heated ventilation air that had ventilated the electronics room and engine room. In the new unit, the ventilation air that cooled the electronics room is first used to cool the alternator and then ventilates the engine room (Fig. 7).

The order in which the engine mounts in the engine room and the alternator are cooled is reversed, so the average temperature might rise inside the engine room. However, this temperature rise around the mounts is prevented by enhancing the velocity and direction of the ventilation air that flows into the engine room.

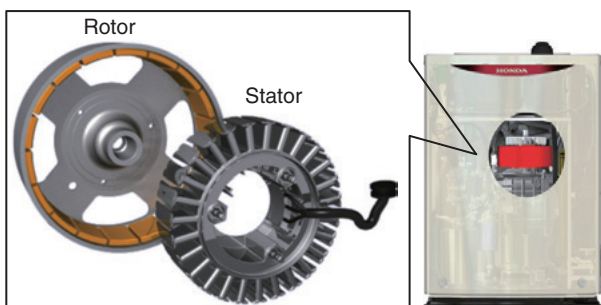


Fig. 6 External view of alternator

Figure 8 shows an example of the simulation results.

The ventilation air is exhausted to the outside of the unit via a ventilation outlet duct with a structure that prevents noise from leaking to the outside of the unit.

This realized efficient internal ventilation, and enabled ultimately reducing the cooling air flow from the previous 35 m³/h to 13 m³/h.

3.2.2. Engine oil cooling system

In the heat recovery system of the 2011 model, the cooling water first performs heat exchange with the engine oil before reaching the exhaust heat exchanger.

The 2006 model had a coil-shaped oil cooler (tank coil-type heat exchanger) inside the oil tank, but the 2011 model uses a configuration that integrates the oil cooler with the oil pan (tank jacket-type heat exchanger) (Fig. 9). This realized efficient heat recovery from the high-temperature

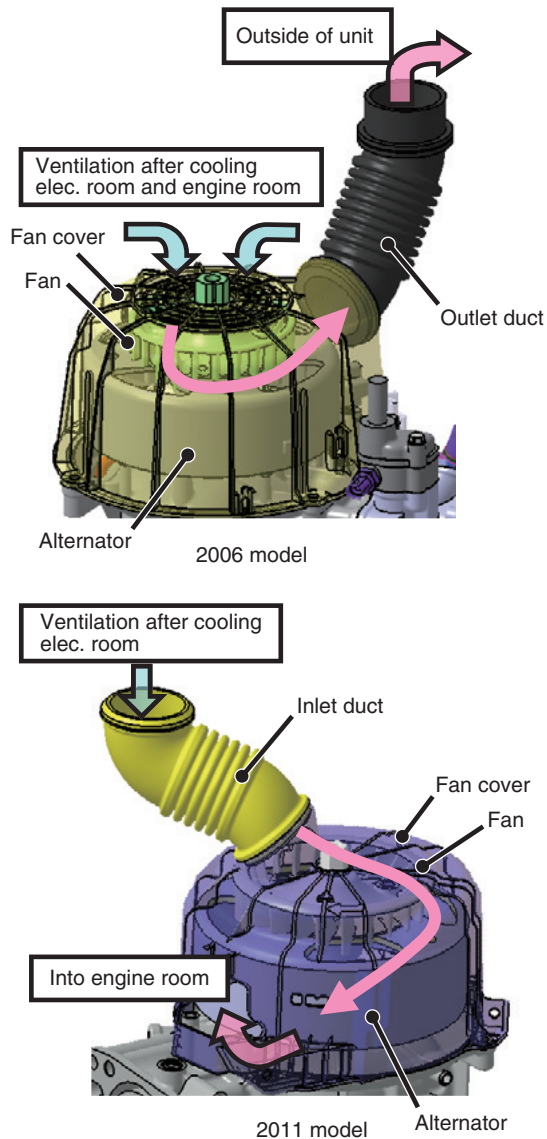


Fig. 7 Comparison of ventilation air flow in 2006 model and 2011 model

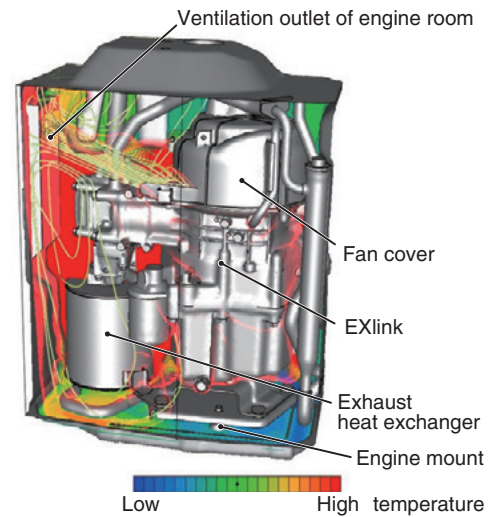


Fig. 8 Calculated flowlines and temperature distribution in engine room

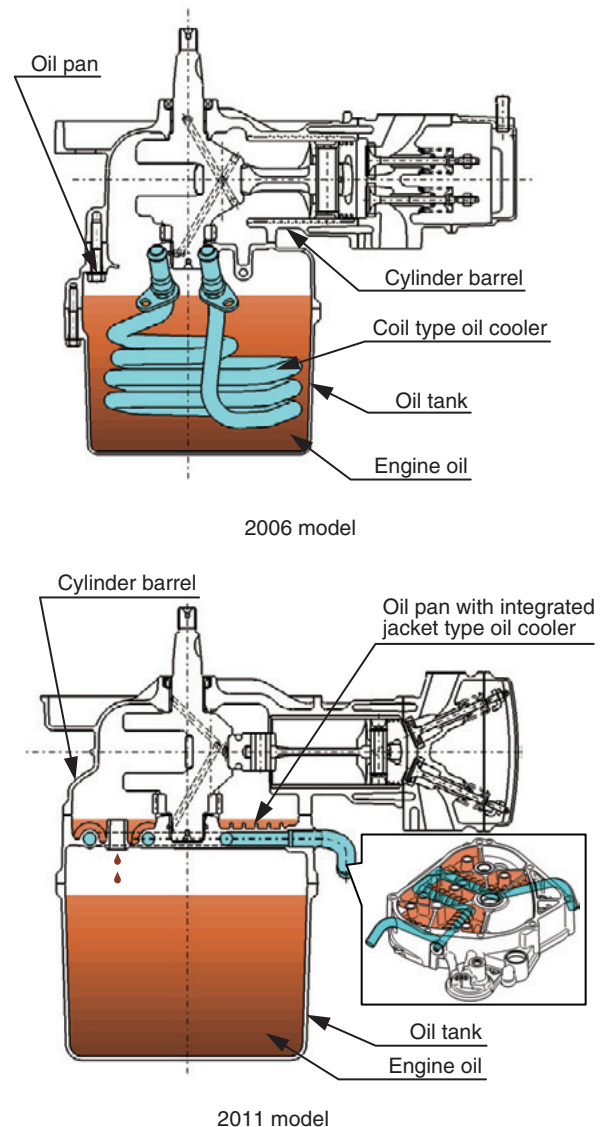


Fig. 9 Oil cooler structure

engine oil immediately after it lubricated the inside of the engine.

3.2.3. Increased heat recovery efficiency and increased overall efficiency

Efforts were made to increase the heat recovery efficiency by reducing the heat energy discarded to the outside of the unit. This realized a 2.7-point increase in the heat recovery efficiency from 63% (LHV) for the 2006 model to 65.5% (LHV), which increased the overall efficiency from 85.5% (LHV) for the 2006 model to 92% (LHV).

3.3. Technologies to Reduce Vibration and Noise

3.3.1. Reducing noise by using EXlink

Use of the high-efficiency EXlink reduced the intake air amount, which enabled reduction of the cubic volume of the intake silencer by 45% compared to the 2006 model. In addition, the reduction in the intake air amount is also advantageous for lowering the exhaust noise. The sound quality was enhanced by reviewing the packaging, and by increasing the muffler volume by 15% compared to the 2006 model.

3.3.2. Reducing vibration by optimization of the linkage layout

Increasing the expansion ratio changes the piston stroke length, so the inertia force due to piston acceleration also increases, which increases the vibration. As a countermeasure, the linkage layout applied a crank rotation angle shorter than 180° to the intake and compression strokes that have short stroke lengths, and a crank rotation angle longer than 180° to the expansion and exhaust strokes that have long stroke lengths⁽⁶⁾⁻⁽⁷⁾. This reduced the calculated maximum inertia force due to piston reciprocating motion by 23% compared to the 2006 model. In addition, changes were also made to the engine layout, and together with other enhancements this reduced the exciting force from the unit to the installation foundation by 40% compared to the 2006 model.

3.3.3. Countermeasures for knocking noise due to shaft thrust loads

Gear-meshing noise was reduced by using a helical gear for the cylindrical gear that synchronize the rotation rate of the eccentric shaft at half, and by supplying an oil jet to the meshing parts. Use of a helical gear generated thrust force in the axial directions of the crankshaft and the eccentric shaft due to the torque reaction force. On the other hand, the torque generated by the cylinder internal pressure and the inertia force around the piston fluctuates over the course of a single cycle, so the gear driving-driven relationship of each shaft alternates. This means that the thrust force alternately inverts, which gives rise to concerns about knocking noise. To address this thrust-knocking noise, a structure was used that applies hydraulic pressure to the crankshaft

in the direction to cancel the thrust force produced by the crankshaft weight and the helical gear, and to both ends of the eccentric shaft. In this way, the direction in which the shaft receives loads does not change even when the gear driving-driven relationship inverts (Fig. 10). Figure 11 shows the relationship between the engine assembly noise and the crankshaft thrust force generated by the hydraulic pressure. As a result, the 2011 model achieved the same engine assembly noise as the 2006 model, which together with the reduced intake and exhaust noise described above, achieved a 1-dB(A) reduction in the overall unit noise to 43 dB(A)/1m.

3.4. Technologies to Reduce Size

3.4.1. Technologies to reduce the engine size

There were concerns that the following points would increase the EXlink engine size.

- Addition of a multiple linkage system and linkage driving gears

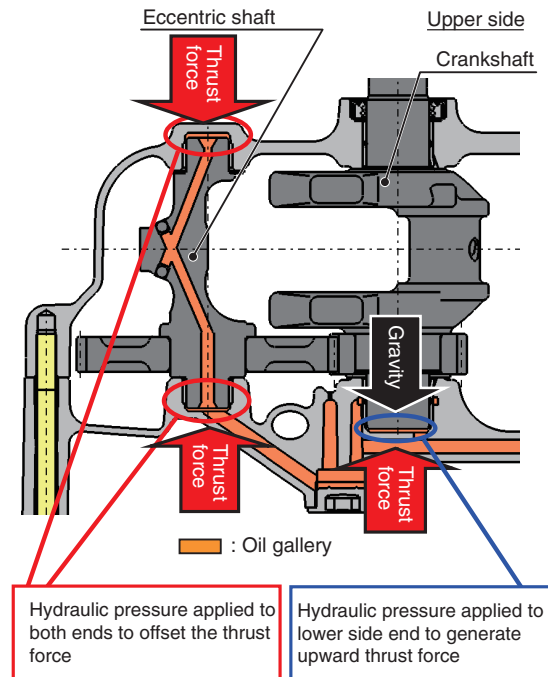


Fig. 10 Oil damping system

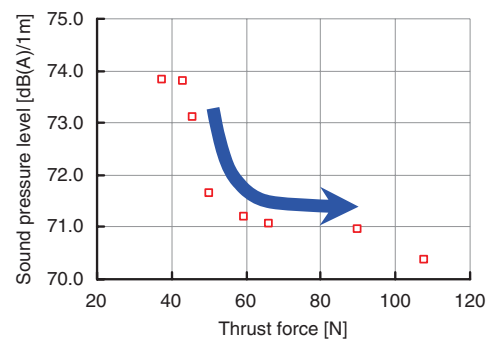


Fig. 11 Relative crankshaft thrust force (by hydraulic pressure) and engine noise

- An apparent super-long stroke due to extension of the expansion ratio

Formerly, the cylinder barrel and the oil tank were separately tightened to the oil pan. However, in order to house this engine in a compact chassis, the structure was modified so that all these parts are jointly tightened, and the crank case external dimensions were kept the same as in the previous model (Fig. 12).

3.4.2. Technologies to reduce the unit size

The engine cylinder layout was changed from diagonal to sideways as viewed from above. This made the unit width dimension the sum of the engine crank case thickness, the sound insulator thickness, and the clearance. The sound insulator was reviewed to achieve the target unit width of 300 mm or less.

The previous engine room sound insulator consisted of a cut piece of soft urethane foam with a constant thickness. Large external dimensions were set to secure the necessary

clearance between the sound insulator and the engine, and holes were opened in the sound insulator in locations where sufficient clearance could not be secured.

Therefore, the materials were changed to a molded felt insulator with a compression molded surface. This secured the necessary clearance in accordance with the unevenness of the engine, and enabled minimizing the holes from which sound can escape, which simultaneously achieved both high quietness and compactness (Fig. 13).

The 2006 model had a unit width of 380 mm excluding protrusions. This was reduced by 82 mm to 298 mm for the 2011 model.

In addition, the intake system parts layout was also reviewed. As a result, the unit height excluding protrusions was reduced by 130 mm from 880 mm to 750 mm, and the volume was also reduced by 33% compared to the 2006 model.

The reduced unit surface area enabled reducing the number of large-sized parts such as panels.

Reducing the unit size increased the chassis stiffness, which enabled elimination of the left side frame and reduction of the number of fastening parts. Ultimately, the number of large-sized pressed parts was reduced from ten to eight, and the overall unit weight was reduced by 11 kg (Fig. 14).

The compact unit size and reduced weight enhanced installation performance, and also provided merits such as reduced heat radiation from the outer panels, shorter wiring inside the unit, and the ability to load more units during transport.

The maintenance directions and the wiring and piping directions during installation were gathered on both sides of the unit. This enabled a reduction in the width of the required space for installation from 950 mm to 650 mm, including the maintenance space, achieving considerable instability.

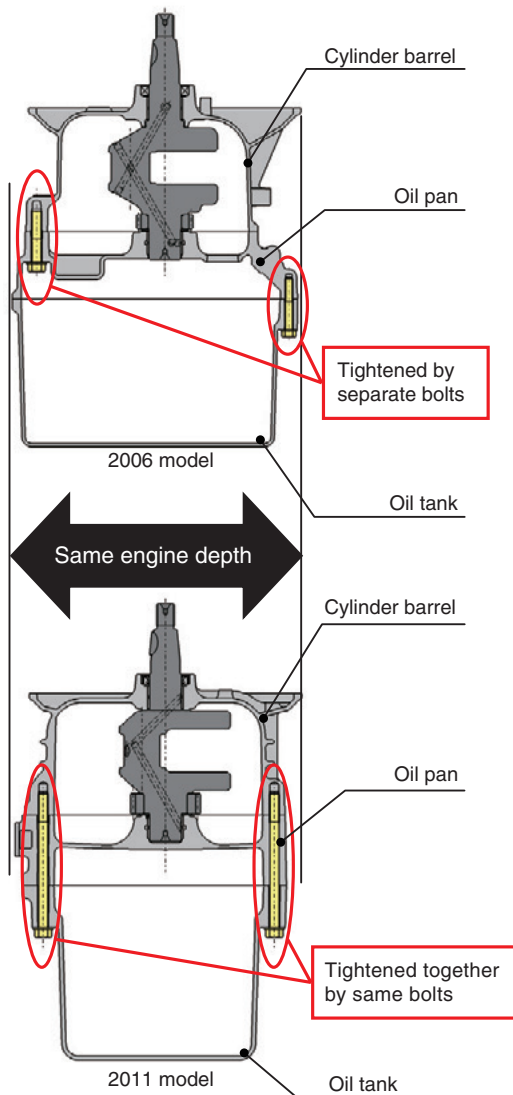


Fig. 12 Engine case tightening structure

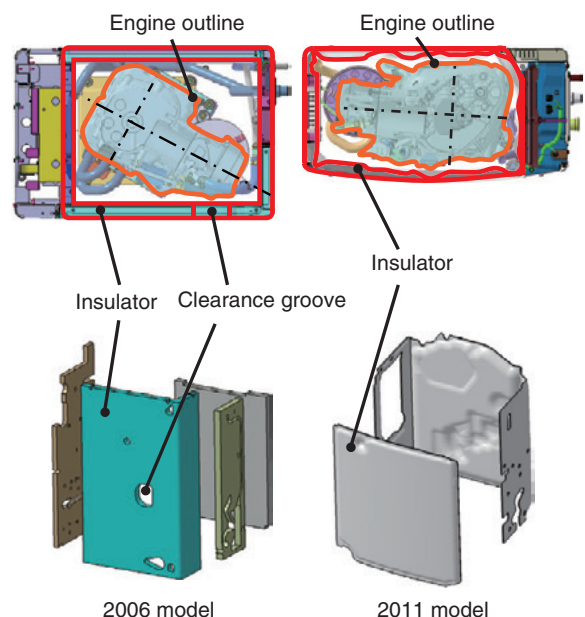


Fig. 13 Comparison of insulator structure

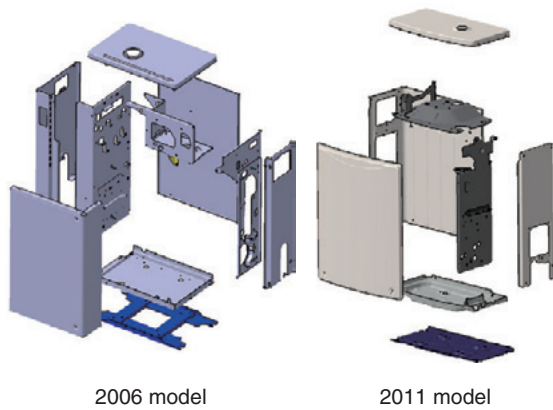


Fig. 14 Comparison of frame and panel structure

4. Conclusion

A micro combined heat and power generation (CHP) unit that uses the EXlink engine was developed. The external view (Fig. 15), product specifications (Table 2) and achieved values are shown below.

- (1) A micro CHP unit equipped with EXlink was developed, and achieved an increase in power generating efficiency of 3.8 points to 26.3% (LHV) and an increase in heat recovery efficiency of 2.7 points to 65.7% (LHV) compared to the 2006 model. The overall efficiency increased by 6.5 points to 92% (LHV), and it was shown that EXlink is useful for enhancing the environmental performance of a micro gas engine CHP system.
- (2) Enhancement of the engine packaging method achieved a smaller chassis size. Specifically, the width was reduced by 82 mm to 298 mm, the height was reduced by 130 mm to 750 mm, and the volume was reduced by 33%, compared to the 2006 model. This realized enhanced installation performance.
- (3) With the use of EXlink, the intake and exhaust systems were also reviewed and gear noise was reduced, which achieved a noise value of 43 dB(A)/1m.



Fig. 15 External view of 2011 model

Table 2 2011 model specifications

Output	Electricity	1 ϕ 3W 202V/101V 50/60Hz 1.0 kW
	Heat	2.5 kW
Power supply		Grid connection by inverter
Heat recovery		75°C hot water
Efficiencies (LHV)	Electricity	26.3%
	Heat	65.7%
Dimensions (LxWxH)		580 mm x 298 mm x 750 mm
Mass		74 kg
Noise		43 dB(A)/1m (JIS B 8627-1)
Starting system		Starter generator

- (4) The compact size enabled integration of large-sized frame parts, and achieved a weight reduction of 11 kg compared to the 2006 model.

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