Technical Paper

Development of 3D95 Engine

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SAA3D95E-1 diesel engine, which has a displacement of 2.4 L and covers the range from 37 kW to 56 kW as well as complies with the European Union's Stage V emission regulations, was developed and introduced to the market. The improvement of fuel economy is an important issue in the aspect of not only the emission regulations but also the social demand. SAA3D95E-1 is incorporated with new technologies and has been developed in consideration of the environment without compromising the durability that is a strength of Komatsu engines. This paper reports on the background of its development and technical features.

***Key Words**: Construction machinery, Diesel engine, Emission regulations, Improved fuel economy*

1. Introduction

Being highly reliable and durable with a broad power range and high thermal efficiency, diesel engines, from small to large, are used as a power source in the industrial field. However, as their negative impact on our environment and ecology has been pointed out, diesel engines came to a turning point. Diesel engines for construction machinery are no exception, and emission regulations for them have become stringent over the years in countries all over the world. Of these, especially Stage V introduced in the European Union (EU) is the leading emission regulations for diesel engines for construction and mining machinery. In addition to carbon neutral being globally promoted in recent years, improved thermal efficiency is a crucial goal for diesel engines to achieve.

To date, Komatsu has developed, manufactured and sold 3.3- to 78-liter diesel engines for industrial use and, this time, succeeded in newly developing the 2.4-liter engine SAA3D95E-1 which has a 37 - 56 kW power range and complies with the Stage V regulations. It is the first time in nearly 30 years Komatsu has added a new model in its engine lineup. This paper reports on the background of the development of the SAA3D95E-1 and its technical features.

2. Trends in emission regulations for diesel engines for construction machinery, and the power range offered by the developed engine

As is mentioned above, new emission regulations for diesel engines for construction machinery, called Stage V, was introduced in 2019 and is now entering a new phase. The trends of emission regulations in Japan, North America and Europe as of present are summarized annually in **Fig. 1.**

The graph in **Fig. 2** shows the change of emission regulations for 37 - 56 kW engines, using the EU regulations as a typical example, from Stages I, II, IIIA, IIIB to V *[1] with the horizontal and vertical axes expressing the limits for nitrogen oxides (NOx) and particulate matter (PM). These regulations have grown more and more stringent in each stage in every three to five years from a macro perspective, requiring a further reduction of about 30% in the regulation limits for main substances such as NOx and PM, each. Furthermore, in addition to emission limits for PM, emission limits for particle number (PN) were included from Stage V.

*1: Stage IV is not applied to 37 - 56 kW range engines.

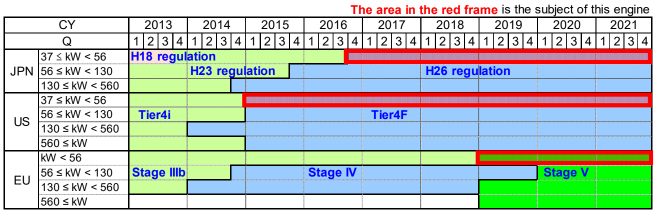


Fig. 1 Trends in the change of emission regulations in Japan, U.S. and Europe

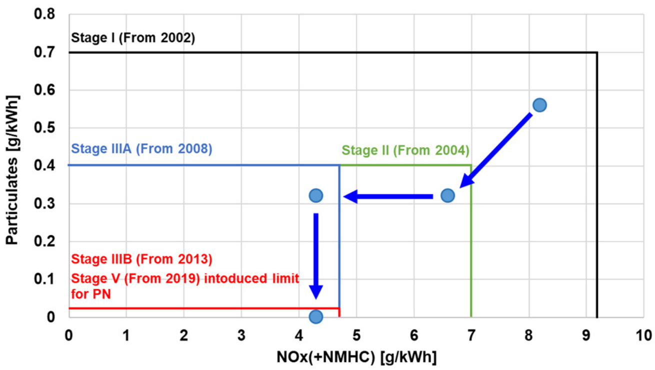


Fig. 2 Changes in the EU emission regulations (for 37 - 56 kW engines)

3. Story behind the development of the 3D95 engine and its aims

Komatsu has developed, manufactured and sold 3.3- to 78-liter diesel engines for industrial use. As can be seen in **Fig. 3**, the 3.3-liter engine SAA4D95LE-6 by Komatsu covers a range as broad as 43 - 90 kW and has large displacement for a 37 - 56 kW range engine. For this reason, it is low in competitiveness in terms of fuel economy and costs compared with its competitions. Moreover, it has been more than 30 years since the mass production of the 3.3-liter base engine, and therefore the engine has needed additional functional parts installed in order to keep up with regulations thus far, which is not suitable in terms of maintainability as well. Also, as discussed earlier, in accordance with the Stage V emission regulations taking effect from 2019 in EU, 37 - 56 kW range engines must be equipped with a Diesel Particulate Filter (DPF) to comply with the regulations. This is how Komatsu initiated to develop the new 2.4-liter engine SAA3D95E-1 with a power range of 37 - 56 kW, which is now introduced in details below.

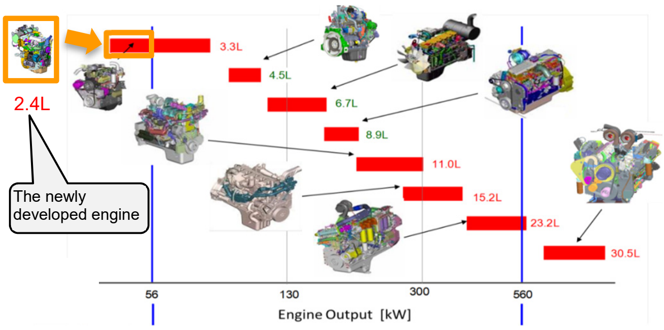


Fig. 3 Displacement and power of Komatsu engines

The SAA3D95E-1 engine was developed particularly for the 7-ton excavator PC78US-11 by Komatsu which was released in November, 2020. For the purpose of creating a competitive engine as a vehicle, engineers specialized in engine design joined from the stage of planning the vehicle concept and provided their feedback on vehicle and engine designs including the power line such as hydraulic pumps for optimization. Also as mentioned previously, the SAA3D95E-1 is a new model developed for the first time in almost 30 years and was designed from scratch including its intake and exhaust system and power cylinders. A team mainly made up of young engineers around thirty years old was formed to elaborate a concept for the new design while thinking outside the box. Sharing opinions with the production department at a deeper level from the initial stage of the engine design served to promote the simultaneous engineering more than ever, improving engine cost effectiveness.

Listed below are the aims targeted to develop the engine.

(1) Improved fuel economy
(2) Compliance with the EU Stage V emission regulations
(3) Reduced engine costs and improved maintainability

Shown in **Table 1** are the main specifications of engines installed in the newly developed and conventional 7-ton excavator models by Komatsu. Also, depicted in **Fig. 4** is the appearance of the Stage V compliant SAA3D95E-1 engine designed for 7-ton excavators.

Table 1 Main specifications of the engines installed in Komatsu 7-ton excavators

		New model	Conventional model
Engine		SAA3D95E-1	SAA4D95LE-6
Displacement	L	2.45	3.26
Number of cylinders		3	4
Bore	mm	95	
Stroke	mm	115	
Compression ratio		17.3	
Combustion system		Direct Injection	
Turbocharger		Fixed geometry turbocharger (with Air-Cooled Aftercooler)	Variable geometry turbocharger (with Air-Cooled Aftercooler)
Aftertreatment system		JPN, US: KDOC *2 EU: KDPF *3	KDOC
Fuel injection system		Electronically controlled common rail	
Number of valves	/cylinder	3 Intake: 2 Exhaust: 1	4 Intake: 2 Exhaust: 2
Valve train		OHV	
Maximum power	kW/min^{-1}	50.7/1900	50.7/1950
Maximum torque	kW/min^{-1}	339/1400	324/1400
Emission Standard	JPN	H26 regulation	
	US	Tier4Final	
	EU	Stage V	Stage IIIB

*2: Komatsu Diesel Oxidation Catalyst

*3: Komatsu Diesel Particulate Filter

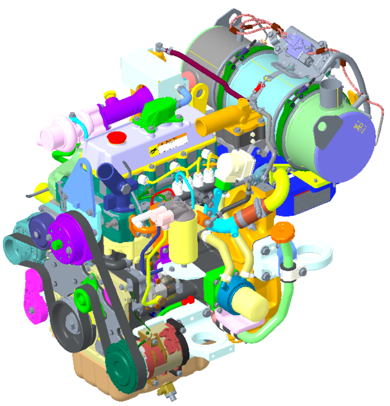


Fig. 4 Appearance of the Stage V compliant SAA3D95E-1 engine

4. Technologies used for the 3D95 engine

4.1 Improved fuel economy

To realize remarkably improved fuel economy compared to the SAA4D95LE-6, the SAA3D95E-1 is incorporated with various technologies which provide reduced displacement and speed, improved combustion, decreased friction loss, etc. As is seen in **Fig. 5**, an approx. 13% improvement in fuel economy on vehicle cycle *4 in total compared to conventional engines. The entire 7-ton excavator achieves an about 28% improvement in fuel economy, which is a great contribution from the improved fuel economy in the developed engine. Introduced below are the key technologies.

*4: Specific fuel consumption measured based on testing methods specified in the Japan Construction Machinery and Construction Association Standards (JCMAS).

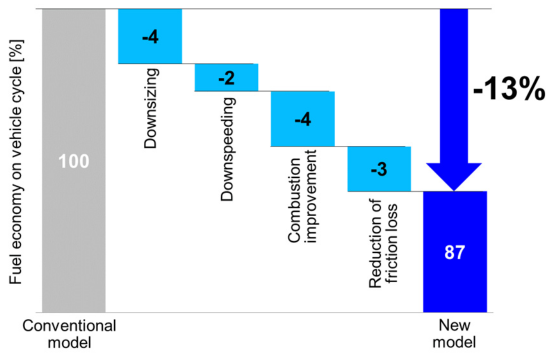


Fig. 5 Improved fuel economy with 3D95 engine

4.1.1 Reduced displacement and speed

Engines with small displacement, in comparison with engines with large displacement offering the same power, are higher in specific output and smaller in displacement, and therefore their parts around the combustion chamber such as the piston, cylinder block and cylinder head can be downsized, providing space savings in the heat dissipation area and ultimately reducing cooling loss. The same is true with mechanical loss. There is a technique intended to improve fuel economy by increasing Pme *5 and boost pressure to reduce engine displacement and consequently realize loss reduction, which is called downsizing. By utilizing downsizing for the development, the SAA3D95E-1 achieves the same power as the SAA4D95LE-6 in ratings on a 7-ton excavator, in spite of its reduced displacement to 3/4, with increased boost pressure approx. 1.4-fold. The use of downsizing resulted in an approx. 4% reduction in fuel economy on vehicle cycle compared to the SAA4D95LE-6. Furthermore, by matching the engine speed at low to reduce losses in the entire engine, the new 7-ton excavator achieves further loss reduction of approx. 2%.

*5: Pme (Mean effective pressure. A parameter used to measure the pressure applied to an engine such as thermal and mechanical pressure.)

4.1.2 Improved combustion

While retaining Komatsu high pressure injection system and Exhaust Gas Recirculation (EGR) system technologies developed for the SAA4D95LE-6, the SAA3D95E-1 engine offers improved thermal efficiency by increasing the maximum cylinder pressure (Pmax) by approx. 30%. Generally, advanced injection timing causes the combustion temperature to rise, increasing NOx emissions. However, raising the EGR rate by about 10% in the high speed and high load areas prevents NOx emissions from increasing. Although raising the EGR rate accompanies an increase in PM emissions, the SAA3D95E-1 engine is able to keep PM emissions at a level similar to that of the SAA4D95LE-6 by increasing the common rail pressure by approx. 25%. On the other hand, due to the increased Pmax, it was necessary to enhance the parts strength for pressure resistance. The SAA3D95E-1 is designed as a high strength and light weight unit by increasing the piston pin diameter by approx. 17%, changing the material of the connecting rod to stronger one and optimizing the structure of the cylinder block and the cylinder head.

Furthermore, the number of injection nozzles and the diameter of the nozzle are optimized to match the combustion chamber in order to boost the mixing of fuel and air. This optimization enables the engine to have an intake air swirl ratio (in-cylinder air swirl motion) approx. 2/3 less than that of the SAA4D95LE-6. The diminished swirl ratio makes it possible to reduce the air flow resistance generated when taking the intake air into the cylinder, and therefore decrease a pumping loss (energy loss caused during the intake and exhaust process). Mean flow rate characteristics (μσ) used to indicate how easily air enters at the intake port is improved by reducing a swirl ratio. Moreover, as shown in **Fig. 6**, the optimization of the intake port shape realized additional improvement in μσ more than for the reduced swirl ratio. As a result, an approx. 20% improvement in μσ is achieved compared to the SAA4D95LE-6.

With these technologies for improving combustion, an approx. 4% reduction in fuel economy on vehicle cycle is realized in total compared to the SAA4D95LE-6.

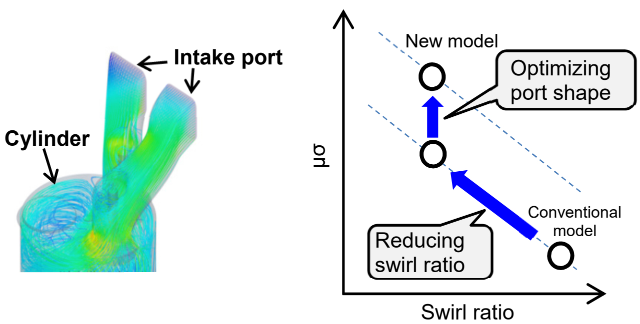


Fig. 6 Optimization of the intake port shape

4.1.3 Reduced friction loss

The SAA3D95E-1 enables reduced friction loss by decreasing the number of cylinders by one from four. In addition, it incorporates the following technologies to minimize friction loss. The use of these technologies for reducing friction loss made it possible to achieve an approx. 3% reduction in fuel economy on vehicle cycle in total compared to the SAA4D95LE-6.

(1) Increase in connecting rod stroke ratio

The value obtained by dividing the length (L) between the center of the large end and the center of the small end of the connecting rod by the crank turning radius (r) is called connecting rod stroke ratio. As illustrated in **Fig. 7**, as this value becomes larger, the rocking angle (φ) of the connecting rod becomes smaller, decreasing piston side thrust (F) and therefore reducing friction loss. On contrary to the benefit, if this value is made excessively large, the overall height of the cylinder block also needs to be large to match the length of the connecting rod, resulting in an increase in weight and costs and also overall height of the engine. We adopted a connecting rod with a maximum length capable of absorbing the above-mentioned negative impact; consequently, the SAA3D95E-1 has a connecting rod stroke ratio that is 8% higher than the SAA4D95LE-6.

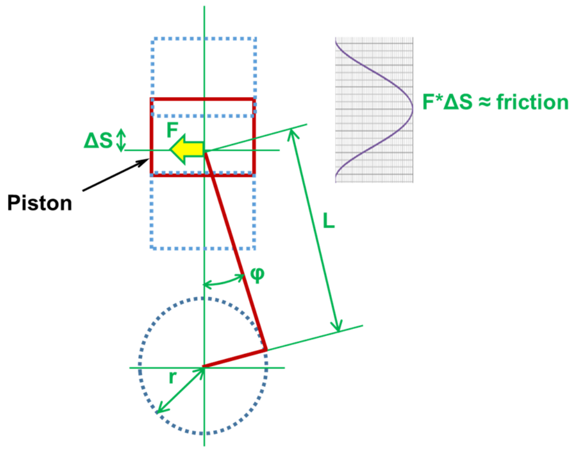


Fig. 7 Connecting rod stroke ratio and piston side thrust

(2) Piston skirt coating

The piston used in the SAA3D95E-1 has its skirt coated with EvoGlide (a coating with polyamide-imide resin having additive agents added to strengthen graphite and base resin) as shown in **Fig. 8**. This reduces the surface roughness of the piston skirt, making the friction coefficient smaller. This also improves initial fitness, contributing to reliability.

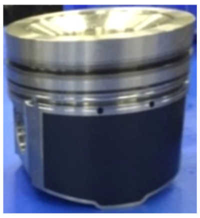


Fig. 8 Coating for the piston skirt

(3) Reduced volume of engine accessories

The cooling system and the lubrication system used in the SAA3D95E-1 are designed by utilizing thermal fluid analysis for optimization in order to realize loss reduction without losing durability. **Fig.9** shows an analysis example of water flow in the water jacket inside the engine. An optimal design was also used for the belt layout to correspond with the reduced volume of accessories. These optimization realized a 20% - 30% reduction each in coolant flow rate, engine oil pressure and belt tension compared to those obtained by the SAA4D95LE-6. Consequently, the water pump driving power and oil pump driving power were reduced almost to half, and the friction loss caused by the belt drive dropped by 30%.

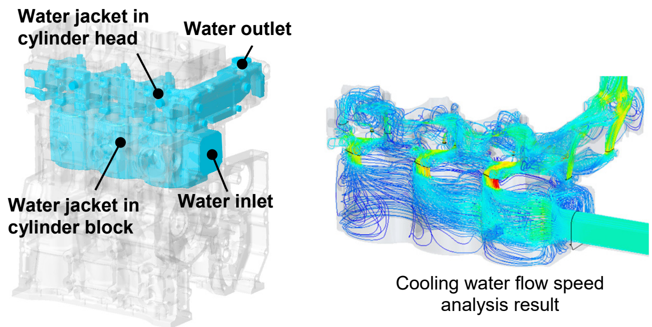


Fig.9 Analysis example of water flow in the water jacket inside the engine

(4) Leak less injector

The SAA3D95E-1 uses injectors with significantly less fuel leakage than those used in the SAA4D95LE-6. Fuel leakage here means high pressure fuel flowing out to the fuel return path through minute gaps, and it leads to a loss of work used to pressurize the fuel. Reduced fuel leakage cuts down on a loss of energy, decreasing the supply pump driving power.

4.2 Compliance with the emission regulations

4.2.1 KDOC and KDPF specifications

The aftertreatment system designed for Japan and North America uses a KDOC muffler capable of providing necessary and sufficient exhaust gas control just as conventional ones. As illustrated in **Fig. 10**, the KDOC muffler is filter-less and therefore advantageous in cutting back on costs required during the life cycle of the vehicle. Meanwhile, for the Europe specification, a dedicated KDPF for this engine was specially developed in order to conform to regulations on PN emissions included in the Stage V. To date, Komatsu has developed KDPFs in various sizes for engines of 56 kW or greater, and the SAA3D95E-1 employs a new small KDPF which incorporates exhaustive improvements while utilizing our long-standing technologies. **Fig. 11** shows the structure of the KDPF.

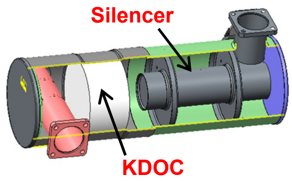


Fig. 10 Structure of the KDOC muffler

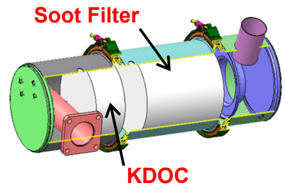


Fig. 11 Structure of the KDPF

4.2.2 Reduced oil consumption

The cylinder in the cylinder block used in the SAA3D95E-1 has improved cylindricity and surface roughness to optimize the combination with the piston ring, realizing a decrease in oil consumption within the cylinder. In light of the fact that the inner surface of the cylinder deforms when the cylinder head is attached, the cylinder was processed with a dummy head installed, which enhanced cylindricity. Given in **Fig. 12** shows appearance of the inner surface of the cylinder after processing. As a result, the SAA3D95E-1 achieves an oil consumption rate nearly half of that with the SAA4D95LE-6. Unburnt oil remaining in the cylinder is regarded as PM in the exhaust gas, and this means reducing oil consumption largely contributes to a reduction in PM emissions.

Because metal components contained in the oil, when burning inside the cylinder, form ashes that accumulate in the KDPF, the KDPF needs to be replaced regularly. While conventional Komatsu engines require KDPF replacement intervals of 4,500 hours, the SAA3D95E-1 offers extended KDPF replacement intervals of 6,000 hours because of the reduced oil consumption, and contributes to cutting down on running costs.

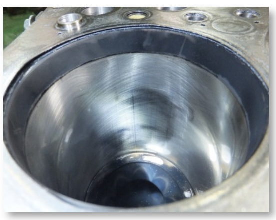


Fig. 12 Appearance of the inner surface of the cylinder

4.2.3 OCV system with a high efficiency breather

The SAA3D95E-1 uses an open crankcase ventilation (OCV) system that exposes the blowby gas exit to the atmosphere in an attempt to simplify the system and reduce costs. As blowby gases are part of the exhaust gas and therefore emission regulations are applicable. Although, upon the employment of an OCV system, it was inevitable to satisfy the emission regulations, the use of a high efficiency breather solved the issue. **Fig. 13** shows an overview of the high efficiency breather. The mechanism is such that the flow speed of generated blowby gases is increased to cause the gases to collide against the non-woven cloth, separating the oil. The non-woven cloth requires no periodic replacement or pressure sensor to detect clogging in the cloth, therefore serving for maintenance-free and running cost reduction.

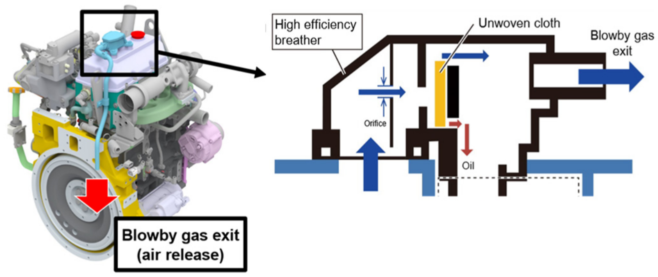


Fig. 13 Mechanism of high efficiency breather

4.3 Improvement of maintainability

With the oil filter, oil gauge, oil filler and fuel filter used for daily and regular inspections arranged on one side of the engine as illustrated in **Fig. 14**, the SAA3D95E-1 for 7-ton excavators offers significantly easy access to these components on the vehicle.

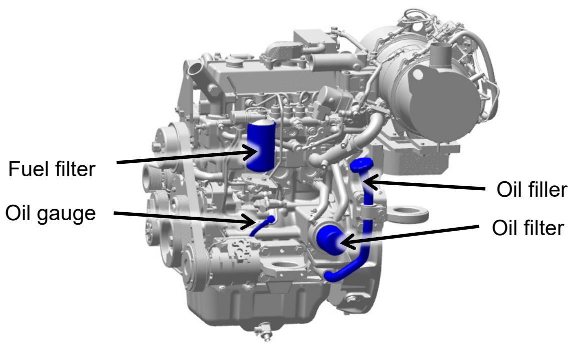


Fig. 14 Arrangement of the filter, etc.

Part consolidation allows the engine to have a drastically smaller number of parts than the SAA4D95LE-6, improving maintainability and ease of assembly. Shown in **Fig. 15** is an example of part consolidation, and the cylinder head serves as an air intake manifold, rocker case and EGR gas passage, each of which is an individual component in the SAA4D95LE-6, and the gear case and water pump case are integrated with the cylinder block.

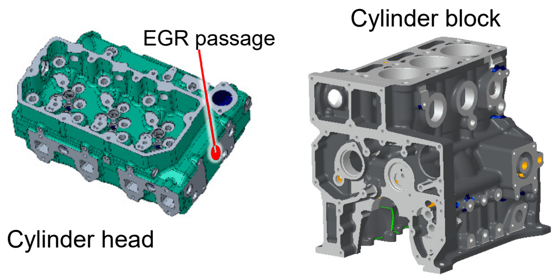


Fig. 15 Appearance of the cylinder head and cylinder block

4.4 Reduced cost

As has been discussed above, the SAA3D95E-1 is designed to be more cost effective than the SAA4D95LE-6 with reduced volume of engine accessories through optimization, smaller number of parts through part consolidation, simplified system, etc. Other than these, the developed engine includes challenging changes such as the use of a fixed geometry turbocharger, fewer exhaust valves and fewer precious metals in the aftertreatment system. Despite drawbacks accompanied by these changes, we succeeded in incorporating these changes in the engine through design improvements and ample performance and quality checks. These approaches realized a 30% reduction *6 in variable cost such as a corporate procurement cost and processing cost (SVC).

*6: Using a KDOC muffler. With depreciation expenses and environmental changes excluded.

4.5 Vibration control

What is unavoidable in three-cylinder engines, due to the asymmetric configuration of the main moving components as shown in **Fig. 16**, is occurrence of force (force couple) that vertically shakes the crankshaft at both ends when viewed from a side. Although this can be resolved by the use of a balancer shaft, driving force for the balance shaft causes an energy loss, worsening to fuel economy. The SAA3D95E-1 uses balance masses on the crankshaft pulley and flywheel in addition to the crankshaft, as can be seen in **Fig. 17**, as a means of solving the problem. With the addition of balance masses, vertical force couple can be converted to horizontal force that is easier for the engine mount to absorb. However, adding balance masses means an increase in volume and weight, and therefore has physical constraints. With engine volume and weight taken into account, the SAA3D95E-1 is designed such that vertical force balances out with horizontal force for an overbalance of 50%.

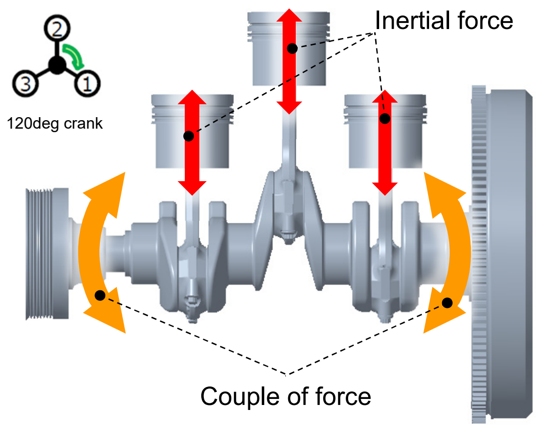


Fig. 16 Three-cylinder engine vibration

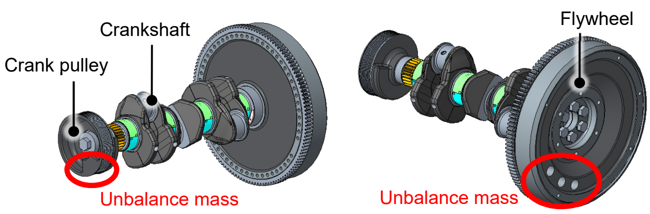


Fig. 17 Appearance of the balance mass

The engine mount was designed and optimized by Engine Development Department working together with Vehicle Development Department in order to achieve both durability and performance as shown in **Fig. 18**. This optimization enables the SAA3D95E-1 to control overall acceleration in the engine mount to be equivalent of or less than that of the SAA4D95LE-6.

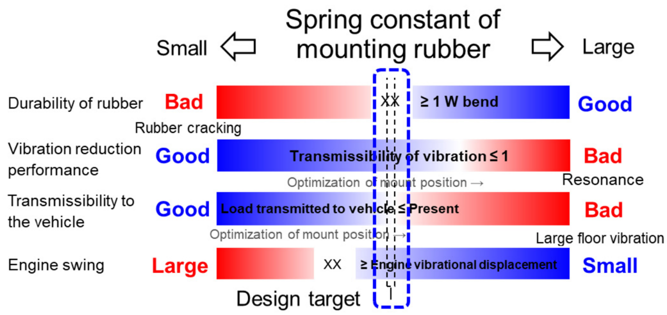


Fig. 18 Optimization of the engine mount

5. Reliability and durability

For the development of the SAA3D95E-1 engine, as well as satisfying all the quality check code for Komatsu industrial engines which incorporate our long cultivated expertise, we implemented adequate reliability and durability testing while working to improve the evaluation test code based on our experience with engines in different sizes. Endurance tests were performed also in a cycle simulating the engine being used in construction machinery, which enhanced the reliability of the vehicle. Consequently, the developed engine went through more than 10,000 hours of bench endurance testing on an engine stand and more than 2,000 hours of vehicle testing and, after the negative findings were handled with certain measures, passed sufficient quality check before moving on to mass production.

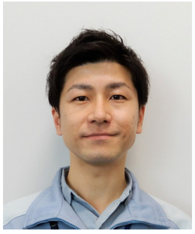
6. Conclusion

We have shared the story behind the development of and technologies used in the new 2.4-liter engine SAA3D95E-1 which complies with the EU Stage V emission regulations and covers a 37 - 56 kW power range. Developing and manufacturing most key components of the engine on our own, we are confident that we succeeded in bringing a new engine that matches the market needs of construction machinery and, moreover, is differentiated from our competitors' products. We believe that the engine, even as a whole vehicle, offers improvements that are appealing to the market such as good fuel economy and enhanced maintainability while retaining the robustness expected of a Komatsu 7-ton excavator.

As the importance of front-loading in product development is emphasized, we always performed simulations without fail before proceeding to actual manufacturing processes as model based development in development of this engine. Since we were dedicated to performing a large number of simulations on too many systems to write in this document, e.g., the structural system, main moving components, valve train, intake and exhaust system, cooling system, lubrication system, combustion and injection system and electric control system, we were able to expand our capability of examination at the initial phase of the development, consequently completing the development project almost in the originally scheduled man-hours for the development. At the same time, however, everything did not work out as planned and it was a long way until the development was complete, and along the way, we faced a considerable number of difficulties and issues to overcome. The experience obtained through this development project has become part of the assets of Komatsu, which will be utilized in further projects and contribute to high-quality manufacturing.

References
[1] "Development of the new 2.4-liter diesel engine for small construction machinery," Japan Land Engine Manufacturers Association 20th Technology Forum Material

Introduction of the authors



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[A comment from the authors]

As the carbon-free movement spreads globally, criticism from society is becoming harsher on engines using fossil fuel. However, given the high energy density of diesel fuel and the advantageous characteristics of diesel engines including durability, reliability and environmental resistance, it is not realistic to replace diesel engines which have been serving as a power source for industrial machinery with something else. We are confident that the developed engine which offers good fuel economy while retaining durability, reliability and environmental resistance meets the needs of society and satisfies our customers with its usability.