

New Three-dimensional Piston Secondary Motion Analysis Method Coupling Structure Analysis and Multi Body Dynamics Analysis

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ABSTRACT

A new piston secondary motion analysis has been developed that accurately predicts piston strength and the slap noise that occurs when the engine is running. For this secondary motion analysis, flexible bodies are used for the models of the piston, cylinder and cylinder head. This makes it possible to quantify the deformations and secondary motion occurring in each area of the engine. The method is a coupled analysis of the structure analysis and the multi body dynamics analysis. The accuracy of the results obtained in the new analysis method was verified by comparing them to measurement data of piston skirt stress and piston secondary motion taken during firing. To measure piston skirt stress, a newly developed battery-powered telemetric measurement system was used. The calculation results were close to the measurement results both for stress and for secondary motion from low to high engine speed. The same comparison was carried out on the vibrational acceleration produced on the cylinder, to determine how piston pin offset and piston skirt rigidity affect piston slap noise. Those calculation results of the vibrational acceleration also closely matched the results of the measurement. With those results, it has been confirmed that this method is an effective tool to make a comparison among different specifications of pistons. This developed method makes it possible to examine the specifications of pistons which are light weighted but still durable with minimal slap-noise.

INTRODUCTION

In recent years, there has been an increasing need to reduce CO₂ emission. For an engine design, to make it more fuel efficient by reducing frictions, pistons need to be light weighted. However, lighter pistons tend to be less durable and cause larger slap noise. It is particularly difficult to make the piston crown area thinner without making it less durable, as it is exposed to firing pressure and high temperature. If the skirt is made thinner, it will not be strong enough and may crack. If it is made shorter, it will increase secondary yawing motion resulting in generation of greater slap noise.

There have already been numerous reports on analysis methods using piston secondary motion simulations to test durability, friction and reduction of slap noise ^{(1) (2)}. The majority of these used a rigid body or pseudo-flexible body

as models of piston and cylinder. In reference literature 2, a flexible body was used as a reduced-size model to improve accuracy of analysis. Its movement was restricted and it was treated as a pseudo-flexible body. However, with these models it was hard to recreate the phenomena of repeating contacts between piston and cylinder with elastic deformations. The results of these analyses were therefore mainly qualitative resulting in making them insufficient for the piston design used to develop new products.

This meant that there was a call for a tool that would produce an accurate quantitative prediction of piston skirt stress and piston slap noise. To meet this demand, a numerical simulation which combines structure analysis and multi body dynamics analysis has been developed. This paper discusses the details of this developed simulation method, explains the measuring technology developed to test the accuracy of our simulation, and gives concrete examples of how our simulation can be used.

PISTON SECONDARY MOTION SIMULATION

OUTLINE OF DEVELOPED ANALYSIS METHOD

Usually, flexible bodies used as samples in multi body dynamics analyses are made using the mode synthesis method. The mode synthesis method recreates elastic deformation with layers of eigenvectors. This can simulate global deformation, but it is difficult to simulate local deformation, that is to say, it is difficult to recreate the contact between piston skirt and cylinder sleeve. In this research, this issue was solved by using new multi body dynamics analysis software that can perform structural analysis by using a direct solver to consider local deformation. Fig. 1 shows a model diagram of multi flexible body dynamics (MFBD), the analysis method used in the multi body dynamics analysis software. Only the high-precision areas require a structure analysis model made using a direct solver. Rigid bodies can be used for all of the other parts, relieving the calculation load.

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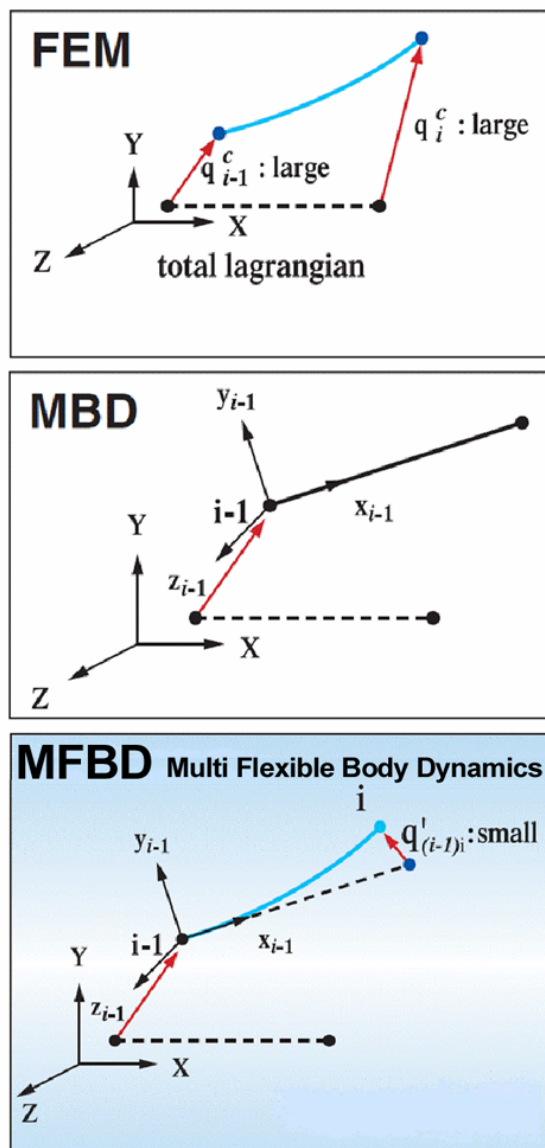


Fig. 1 Coupled analysis method of structure analysis and multi body dynamics analysis ⁽³⁾

Specifically, the finite element method (FEM) is used to make a flexible body model of piston, cylinder, crankcase and cylinder head, and a rigid body is used to make the rest of the models. The multi body dynamics analysis software is then used to carry out a combination of structural analysis and multi body dynamics analysis. The model does not apply EHD (Elasto Hydro Dynamics) for the contact model between the piston and the cylinder sleeve, but use the contact stiffness coefficient and the damping coefficient in this research.

FLEXIBLE BODY

In this analysis method, it is necessary to make the flexible body models of a piston, a cylinder and a crankcase to be reflected with the detailed shapes under firing condition. The deformation of inner wall of the cylinder is analyzed through simulation for the cylinder bolted on the crankcase with the cylinder head. Regarding thermal deformation, the amplitude of deformation is calculated based on the SETC2011

temperature distribution, which is estimated from the actual measurement data, and the data of linear expansion coefficients. This enables a flexible body to be built so as to make the inner wall of the cylinder to be deformed in the same way as one in a real engine. Fig. 2 shows the FEM model.

For the piston, a three-dimensional model is used to reproduce its actual skirt shape by having the elliptical shape in circumferential direction and the tapered shape in vertical direction. The heat-based deformation of a real piston is reflected by carrying out heat transfer analysis and heat stress analysis. Fig. 3 shows the piston FEM model.

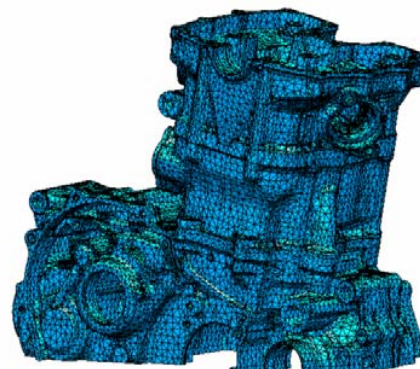


Fig. 2 Cylinder block FEM model

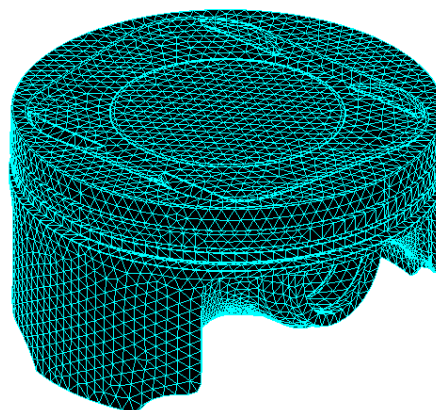


Fig. 3 Piston FEM model

OUTLINE OF SIMULATION

A multi body dynamics analysis model is built reflecting the engine specifications, including FEM models shown on Figs. 2 and 3. For the models of the piston pin, the connecting rod and the crankshaft, which are not recreated with FEM models, the mass, the center of gravity and the moment of inertia have been calculated in advance through three-dimensional models. Those numerical values are then applied for a rigid body, that have been prepared earlier, to calculate the secondary motion. Fig. 4 shows the results of calculations for the deformation and stress of the piston. After firing pressure reaches at its maximum, the piston skirt on the thrust side hits the sleeve, causing large deformation on the piston skirt. However, as the piston pin is modeled from a rigid body, the effects on piston pin deformation are not considered. Fig. 5 shows the results of the calculations for stress contours in the cylinder sleeve. The direction of the piston thrust changes at bottom dead center. The figure

shows, at that point, the piston skirt pushes against the cylinder sleeve causing stress.

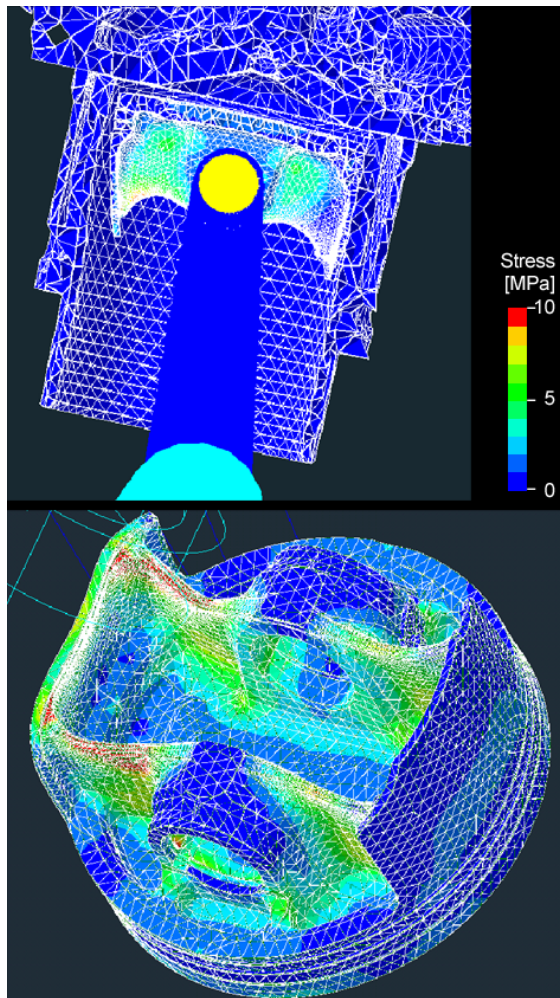


Fig. 4 Calculated deformation and stress of piston

RESULTS OF CALCULATION AND ITS VERIFICATION

ITEMS OF VERIFICATION

The calculation results from the simulation were compared with the measurement results during the engine firing. Specifically, the piston skirt stress and the piston behavior generated during firing were verified.

MEASUREMENT SYSTEM FOR PISTON STRESS

One of method to measure piston stress and temperature is to set up a link mechanism in the engine. This is generally referred to as the “link method”. The link method consists of attaching a link mechanism that puts the lead next to a connecting rod and taking out the lead outside of the engine. However, the engine for the motorcycles is driven in the high rotational speed and is more compact compared with the engine for the four-wheeled vehicles. There are issues in arrangement and durability of the link mechanism when the

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link method is applied to the engine for the motorcycles. Therefore, a telemetric measurement system was applied to this research.

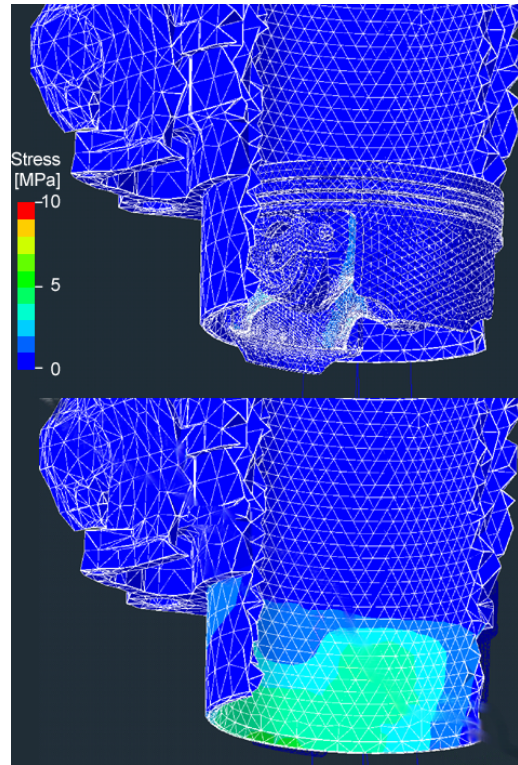


Fig. 5 Calculated stress of cylinder sleeve

In general, telemetric measurement systems are used as follows to measure piston skirt stress. A strain gauge is attached to the inside of the piston skirt to measure stress. A transmitter is attached to the connecting rod and the lead from the strain gauge is inserted into the transmitter. The transmitter is powered by a built-in generator or an external source. A receiver is set up near the engine to record signals sent by the transmitter from the strain gauge. Generally, the connecting rod for the transmitter is specially designed to fit the shape of the transmitter.

A new telemetric measurement system was built for this research. This system was more versatile than standard telemetric measurement systems and the transmitter was battery-powered. This system is unique in four ways. First, it does not require specially-designed connecting rods and pistons. Test pieces can therefore be prepared by partial remodeling of mass-produced parts. As a result, shortening time from the preparation for the test parts to implementation of the measurement was attempted. Second, the telemetric system itself is also not specially designed: it is a versatile system that is both inexpensive and highly efficient. Third, the telemetric system runs on a battery rather than using a built-in generator or inductive power supply. Fourth, the wire to the piston runs through the piston pin, preventing the lead from getting twisted. This prevents the lead from being disconnected during firing and allows for stable measurements during high rotation. Fig. 6 shows the system built for this research. The strain-measuring transmitter is a Datatel dt1001T-ST, a commercial model. Precision testing was performed on test pieces before telemetric strain measurement was carried out. Several