

Development of Simulation Technology for the Dynamic Behavior of Crankshaft Systems in Motorcycle Engines

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ABSTRACT

In order to improve durability and marketability of an engine and reduce the development period, crankshaft system simulation technology was developed.

A crankshaft and a crankcase are modeled using the Finite Element Method (FEM). The models and a calculation model of the hydrodynamic reaction force of bearings are linked and the crankshaft behavior is calculated using numerical integration within the time domain. This simulation technology enabled accurate prediction of crankshaft behavior and stress through the high operating speeds that characterize motorcycle engines.

1. Introduction

Today's market demands that high-performance motorcycle engines with reduced weight and more compact dimensions be developed and that they be developed in a significantly shortened period of time. Since the key parts of engines, such as the crankshafts, connecting rods and pistons, have a major impact on the durability, output characteristics and noise and vibration of these engines, it is absolutely essential for the specifications of the parts to reach a level of maturity during the initial stage of development ⁽¹⁾.

The crankshaft held by the crankcase bearing receives the explosion force and inertia force exerted from the piston through the connecting rod in each cycle.

This load is generally at 10^4 N and higher, and it acts cyclically with each cycle. Resonance is induced, and an excessively high bending load and torsional moment are exerted on the crankshaft with this load especially at high engine speeds. In order to create lightweight and compact engines that will function under these severe conditions, the behavior of the crankshaft, including the pistons, connecting rods, and ACG rotors, is identified and each part must be designed for those conditions.

Based on this background, the authors have developed a simulation technique for calculating very precisely the stress that occurs in the crankshaft under firing operation conditions.

2. Stress Occurring at High Engine Speeds Operation

Fig. 1 shows the structure of the V type, 2-cylinder, 4-stroke engine used in this research. As shown in the figure, this engine has two connecting rods for each pin journal, and the cylinders have a 90-degree phase angle.

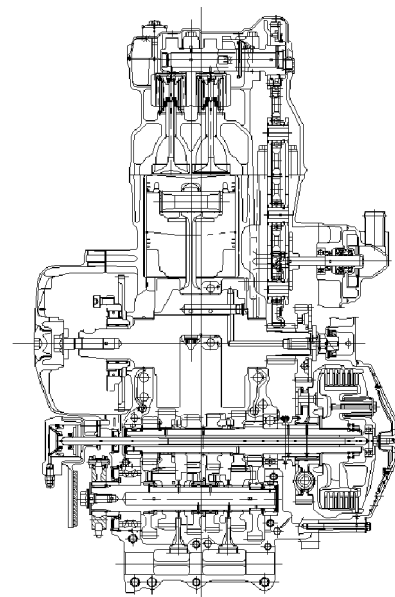


Fig.1 Engine structure

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The stresses that occur in the pin journal fillet area of the crankshaft under the firing operation conditions was measured using strain gauges.

Fig. 2 shows the locations of the measuring points.

Fig. 3 shows the stress amplitude extracted from the stress values obtained for each engine speed.

The following can be said about these results.

- (1) Compared with low engine speeds, the stress amplitude increases significantly at high engine speeds.
- (2) At specific engine speeds, the stress amplitude indicates a maximum value.

The following two factors are likely the causes of the stress amplitude occurring in these areas:

- (1) The inertia force of the reciprocating part acts upon the crankshaft during each cycle
- (2) The load produced by the pressure inside the cylinders acts upon the crankshaft through the piston and connecting rod during each cycle.

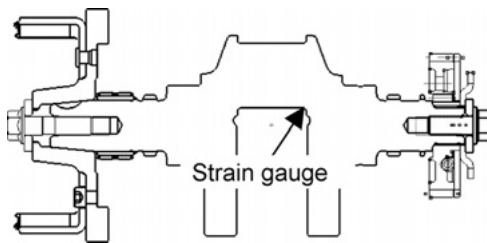


Fig.2 Stress measurement points

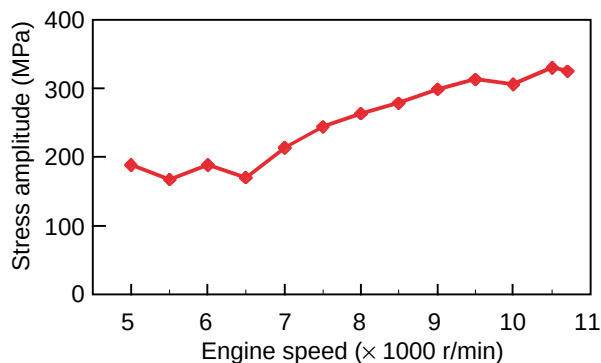


Fig.3 Stress amplitude

3. Static Stress Analysis

In order to analyze the causes for the increase in the stress amplitude at high engine speeds and for the peak stress amplitude exhibited at specific engine speeds, the stress calculation under the static conditions was performed using the finite element method.

Fig. 4 shows the finite element model and the boundary conditions used for the static calculations.

5,000 rpm was selected as the low engine speed and

10,800 rpm was selected as the high engine speed.

Fig. 5 shows a comparison between the static calculation results and the experiment results.

At low speeds, these two sets of results are virtually equal. However, at high speeds, the experiment results were 52% higher. It is considered that the stress amplitude increased at high engine speeds as a result of the dynamic behavior, which occurred in the crankshaft at these engine speeds.

This indicates that adequate precision cannot be obtained using this kind of static calculation method to design the strength of the crankshafts used at high engine speeds.

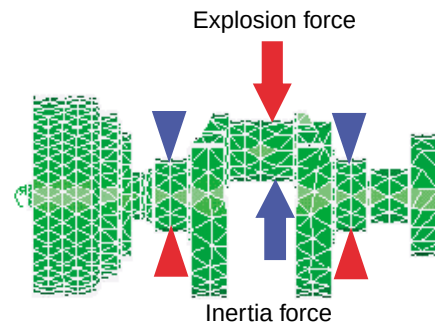


Fig.4 Static FEM model and boundary conditions

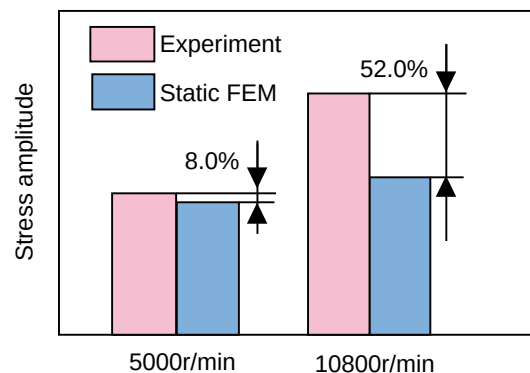


Fig.5 Comparison between experiment measurement and static FEM

4. Dynamic Calculation Methods

The numerical integration method in the time domain, which is widely employed, was used for simulating dynamic behavior. Fig. 6 shows the steps for this calculation method.

The calculation method consists of the following four parts.

- (1) Generating part of finite element data
- (2) Generating part of behavior
- (3) Generating part of oil film pressure
- (4) Generating part of stress

4.1. Generating part of Finite Element Data

The finite element data was generated by the automatic element generating function of a software program available on the market using a 3D solid model. Since the data obtained by this process has a substantial degree of freedom, the modal reduction method was used to eliminate the degree of freedom which was not required for the purposes of the analysis, and the degree of freedom of the finite element data overall was reduced.

4.2. Calculation of Behavior

Fig. 7 shows the simulation model of the behavior calculation. This model consists of the structural elements and the load elements that make the connections between the structural elements.

The following components were modeled.

- Crankshaft Finite element model
- Crankcase Finite element model
- Piston Rigid body model
- Piston-pin Rigid body model
- Connecting rod Rigid body model

The load elements were defined into three categories as follows.

1. In the parts components, a non-linear load is defined for relative displacement, and so on. By this way, the contact of the connecting parts is expressed.
2. The load created by the pressure inside the cylinders is exerted on the pistons and the head part of the cylinder head. The pressure inside the cylinders obtained by actual measurements is used as a numerical formula for the function of the crank rotation displacement angle.
3. Torque is applied in the reverse direction of rotation to the power output gear at the top of the crankshaft. The engine's operation speed for the calculation is determined by adjusting the magnitude of this torque.

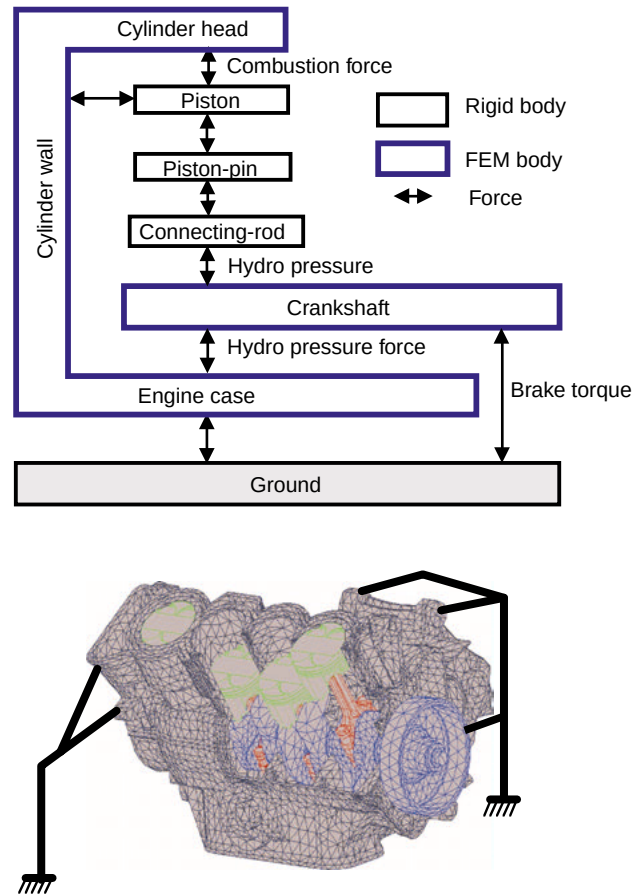


Fig.7 Simulation model

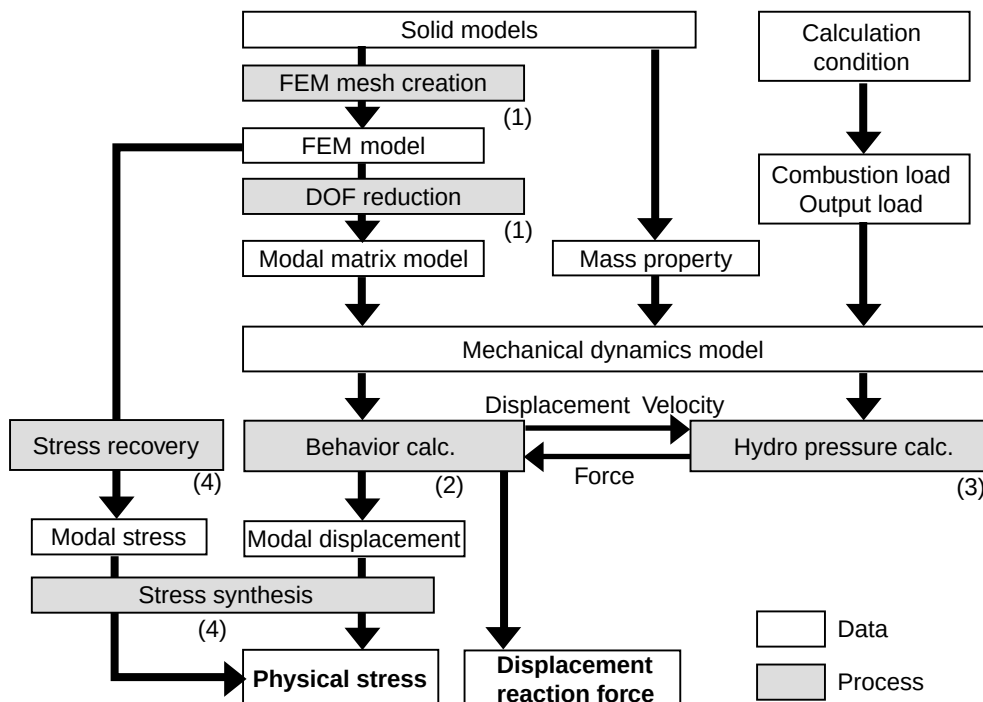


Fig.6 Analysis flow

4.3. Calculating Part of Oil Film Pressure

Based on the fluid lubrication theory, the load calculated from the pressure distribution resulting from the wedge force action and the squeeze force action of the oil was applied between the crank journals and the crankcase bearings and between the crank pin and the connecting rod large-end bearing. It was necessary to create a particularly exact model because it influences directly to the deformation behavior of the crankshaft and the behavior of the journal's axial center.

4.4. Calculating Part of Stress

The stress at each point in time was calculated from the displacement for each mode at each point in time, which was obtained from the behavior calculations, and from the crankshaft stress of each unit mode. At time "t", the displacement of the "i-nth" mode is represented by "ait", the stress of the "i-nth" mode is represented by " σ_i ", and the stress " σ_t " at time "t" is defined by the following formula:

$$\sigma_t = \sum ait \cdot \sigma_i$$

Since no static substitutions are involved during processing, this technique has two advantages: a high accuracy for the solution can be obtained, and the calculation time and data volume can be reduced when the stress at each of many different points in time is calculated.

5. Comparison of Calculation and Experiment Results

The stresses in the crank pin fillet shown in Fig.2 were compared using the aforementioned type 2-cylinder engine to verify the calculating results.

5.1. Engine Operation Conditions

The engine was operated from 5,000 rpm to 11,000 rpm by the full load driving firing.

5.2. Stress during One Cycle at Low Engine Speeds

Fig. 8 shows the results obtained by comparing the stresses of the crank pin fillet area at an engine speed of 5,000 rpm.

The stresses of the crank pin fillet in the above operation condition begin to generate significantly immediately after the crank angle of 0 and 450 degrees.

From here, it was found that the stresses of the crank pin fillet were dominated by the pressure inside the cylinder.

5.3. Stress during One Cycle at High Engine Speeds

Fig. 9 shows the results obtained by comparing the stresses of the crank pin fillet area at an engine speed of 10,800 rpm.

Compared with low engine speeds, it is clear that vibration is generated in the stress waveforms. Additionally, it can be seen that the absolute value of the stress increases significantly by the vibration causes compared with low engine speeds.

5.4. Comparison of Correlation

Based on the stress waveforms of the crank pin fillet

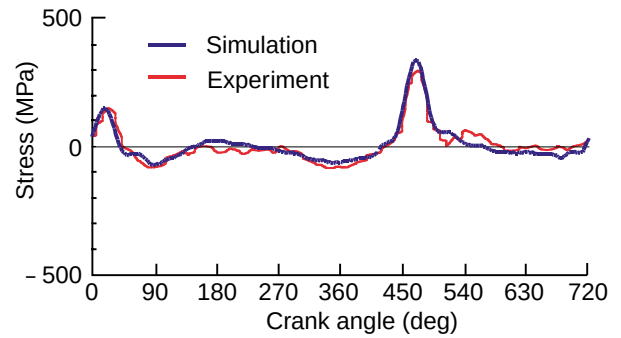


Fig.8 Comparison of stress at 5000r/min

during one cycle as shown in Figs. 8 and 9, it can be stated that the calculation and experiment results correspond very closely. Fig. 10 shows the stress amplitude of the crank pin fillet versus the engine speed for both the calculation and experiment results.

In each engine speed range, it can be stated that the stress of the calculation results of the crank pin fillet area stress practically coincide with the experiment results.

From the above mentioned data, the developed simulation technique verified that the numerical model for the behavior of the crankshaft system was highly accurate.⁽³⁾

Moreover, the effectivity of this simulation technique was verified even in high engine speeds; that was the feature of the motorcycle engine which had been difficult to simulate up to now.

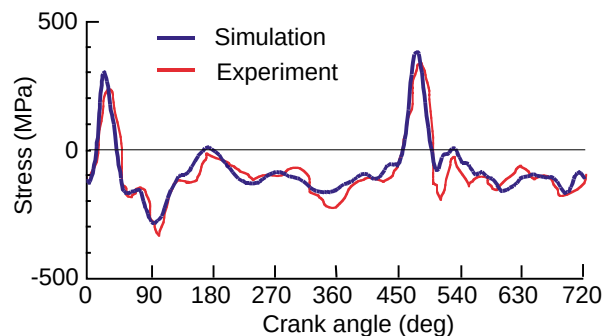


Fig.9 Comparison of stress at 10800r/min

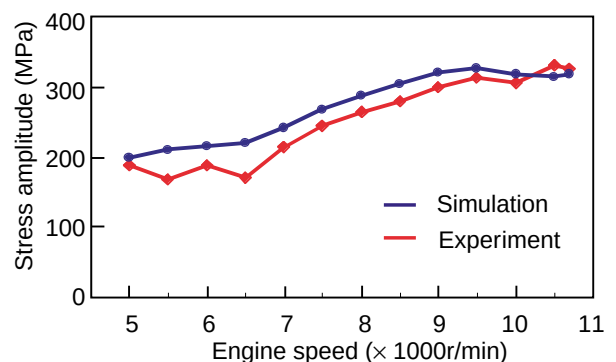


Fig.10 Comparison of stress amplitude

6. Conclusions

- (1) A numerical analysis technique was constructed using the numerical integration method in the time domain that linked the oil film pressure calculation of the bearings with the models of the crankshaft and crankcase using the finite element method.
- (2) Applying the technique to motorcycle engines, it was found that the simulation technique can be used sufficiently in the design stage because it faithfully simulates the stress occurring in crankshafts even at high engine speeds.

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