

A Method for Measuring the Excitation Forces Inside Engines

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ABSTRACT

This paper presents a method for directly measuring the excitation forces exerted on the main bearing journal from the crankshaft. A method was developed for obtaining the amplitude and direction of the constantly changing excitation forces, which had not previously been accomplished. The excitation force direction and absolute value are obtained when the relative error between the strain during actual operation obtained from multiple strain gauges affixed to the inner surface of the main bearing journal and the strain estimated from calibration curves is at a minimum.

1. Introduction

The excitation forces acting in a powertrain, comprising the engine and the transmission, and particularly those excitation forces in the engine exerted by the crankshaft on the main bearing journals during operation, have an important effect on crankshaft rumble, and are therefore critical parameters.

There has previously been no method for directly measuring the magnitude and direction of the excitation forces. Although there has been considerable research leading to various proposals that have focused on indirect measurement methods such as determining the magnitude or direction from vibration measurements or identification using transmission coefficients, direct measurement is still desirable, particularly from the point of view of accuracy.

When measuring directly, it has been conventional wisdom to assume that the direction of the excitation force is fixed, and the value calculated from the calibration curve for a bolt or strain gauge is used as the excitation force. However, in actual running engine, the magnitude and direction of an excitation force is constantly changing. A method for directly measuring the magnitude and direction of an excitation force has now been developed.

2. Method for Measuring Excitation Forces

2.1 Outline of the Measurement Method

The target of this measurement method is to determine the excitation forces acting on the main bearing journals that are generated by the crankshaft during engine operation. The excitation forces are determined by obtaining values through first calibrating the relationship between the output of four strain gauges located on an inner surface of each main

bearing journal and the load at each crankshaft angle. Then the excitation forces are determined using the calibrated values and the strain gauge output that is obtained during engine combustion.

2.2 Test Engine

A Civic 4-cylinder engine was used. The major specifications for this engine are presented in Table 1.

2.3 Measurement Procedure

The following procedure was implemented for measuring the excitation forces:

(1) Calibration Test

Strain measurements were taken with a constant radial load applied to the main bearing journals.

(2) Calibration Curve Calculation

A calibration curve was created for each strain gauge, the horizontal axis being the calibration load on the main bearing journal, and the vertical axis being the calibration sensitivity vector.

(3) Strain Measurements during Engine Operation

Simultaneous measurements of the strain on each main

Table 1 Test engine specifications

Type	Water-cooled, in-line four-cylinder
Valvetrain	SOHC 16 valves
Displacement	1493 cc
Bore/Stroke	75.0 mm / 84.5 mm
Compression ratio	9.4 : 1
Maximum power	105 PS / 6400 rpm
Maximum torque	13.6 kgm / 4500 rpm

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bearing journal were taken while the engine was operating.

(4) Excitation Force Calculation

The direction and absolute value of each excitation force was calculated from the relevant calibration curves.

2.4 Calibration Test Method

The test engine block was mounted with a jig on a tensile/compression tester as shown in Figs. 1 and 2, and a static load was applied to the main bearing journals via a load cell and calibration tool.

Strain gauges were attached, as shown in Fig. 3, at four positions around each main bearing journal 45° from the journal mating surface in consideration of the load frequency, direction change, sensitivity, etc.

Each main bearing metal was machined as shown in Fig. 4 to provide pockets for mounting the strain gauges.

The effect of heat on the measurement was eliminated by using a strain gauge with temperature characteristics appropriate for use with aluminum, and by using the 1-gauge, 3-wire connection method.

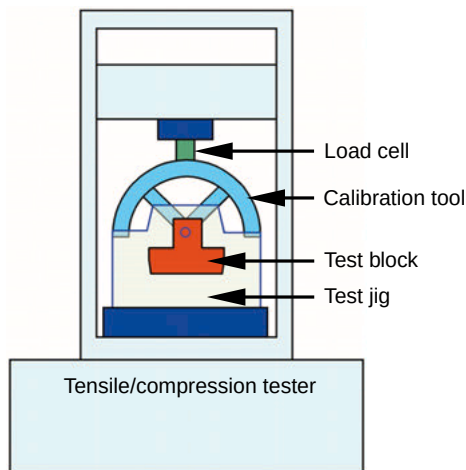


Fig. 1 Calibration test device

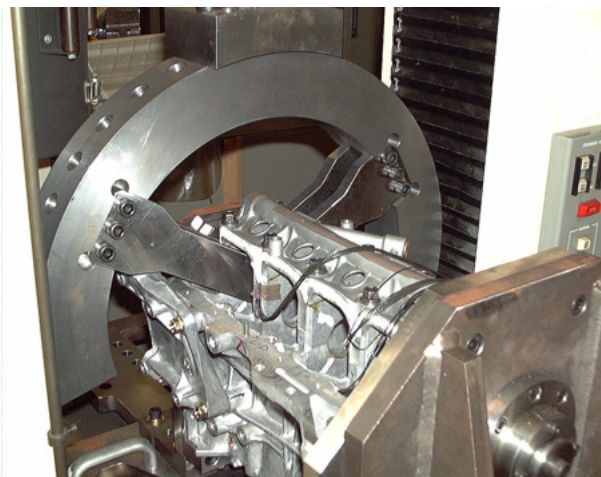


Fig. 2 Calibration jig

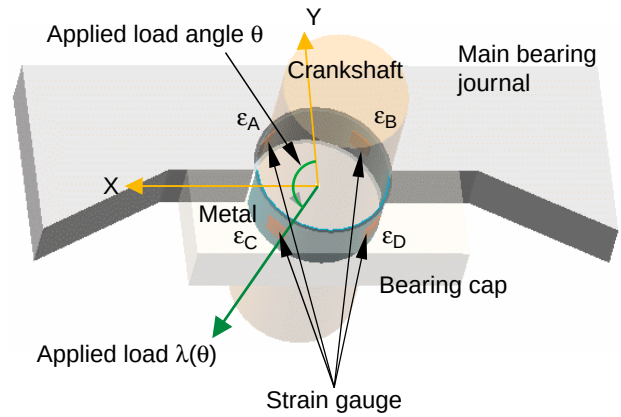


Fig. 3 Attached Strain Gauges and Applied Load

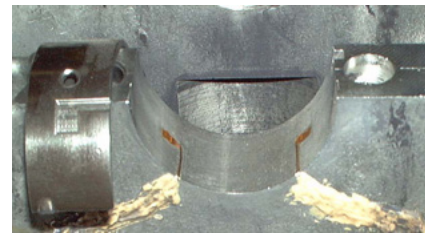


Fig. 4 Strain gauge attachment

The load applied was from 0 to 20,000 N. Measurements were taken every 500 N, in 10° increments from 0° to 360° . Special care was taken with machining the main bearing metals as the shape had a large effect on the oil film thickness. FEM analysis was applied to investigate the machined shape so that changes to the roundness of the internal surface of the main bearing journal could be minimized. Fig. 5 shows the difference between the circumscribing circle and inscribing circle concentric with the reference circle that was determined by the least-squares method applied to the measured values. Table 2 and Fig. 6 give the FEM analysis results of the machined shape. A high concentration of stress was apparent around the initial shape of the machined area of the bearing metals. Thus, these were not adopted for testing. However, by correcting the shape of the machined area, the roundness of these parts was roughly equivalent to that of the mass-production parts and a relatively uniform stress could be obtained. Therefore, the parts with the modified machined area could be used in the tests.

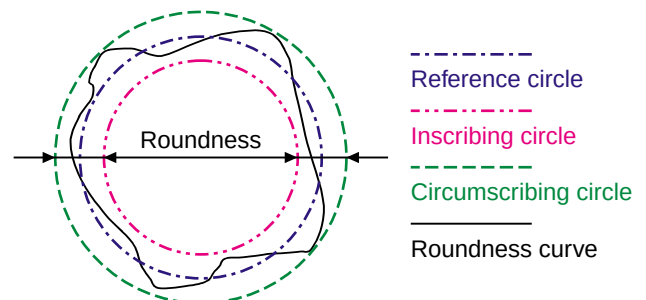


Fig. 5 Roundness measuring method

Table 2 Roundness measurement result

	Roundness (μm)
Mass-produced metal	10.25
Successful notch	9.05
Failed notch	20.01

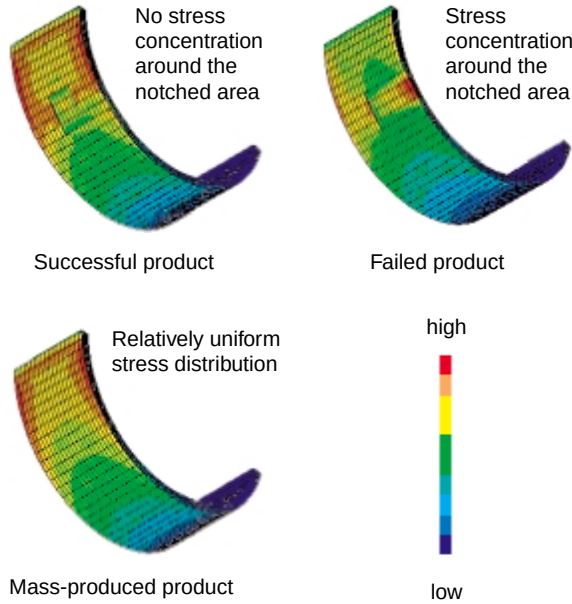


Fig. 6 FEM analysis of bearing metal (Stress distribution)

2.5 Calculating the Calibration Data

2.5.1 Calibration Data Measurements

The measurement results for this calibration test are shown in Fig. 7. The strain output for load exhibits good linear characteristics.

Thus, we decided to use the calibration sensitivity vector determined by the least-square method as the calibration data. Considering the possibility of non-linearity in the high-load

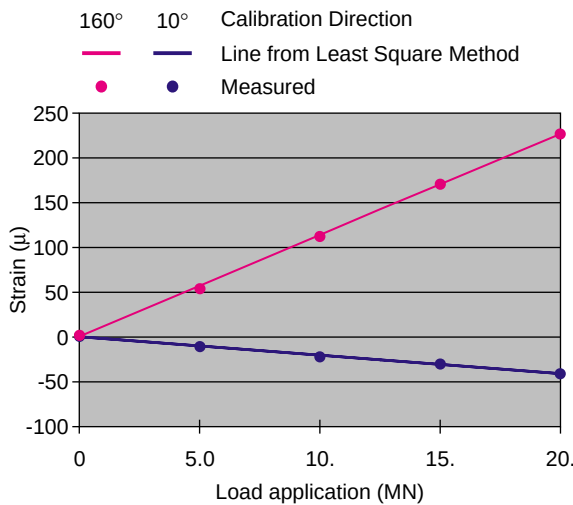


Fig. 7 Calibration test result (for 10° and 160° load direction)

range, calibration data were determined with a load from 0 to 20,000 N. The load direction is defined according to the coordinate system shown in Fig. 3. Calibration was carried out every 10° of crankshaft rotation. However, since a resolution of 1° was required for calculating the excitation forces, it was converted by Lagrange interpolation to calibration data for 1° increments.

2.5.2 Calibration Curve Calculations

The calibration curves shown in Fig. 8 were constructed by interpolating and plotting the calibration sensitivity vector that had been obtained from the test results for an applied calibration load direction from 0° to 360°.

Generally, when there is a perpendicular force applied to a structure like a main bearing journal, we can expect the strain distribution to be like that shown in Fig. 9.

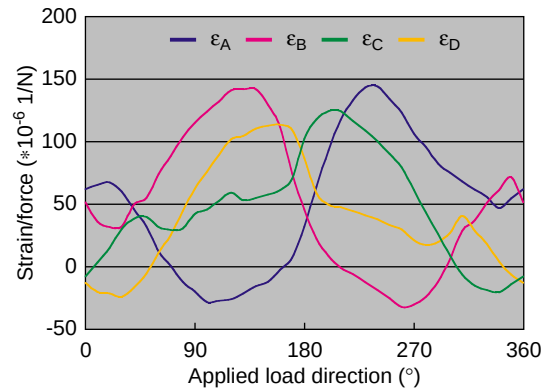


Fig. 8 Calibration curves

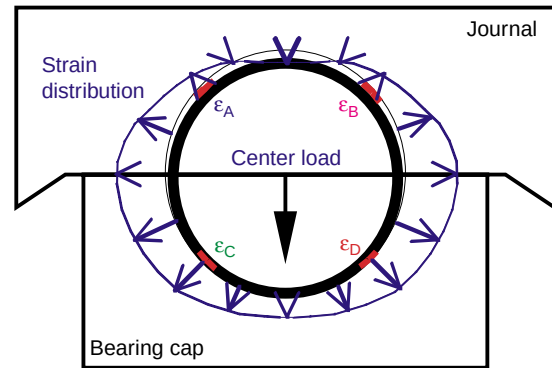


Fig. 9 Strain distribution for a vertical load

This is nearly symmetrical to the right and left of the applied load, but with the journal block side having slightly higher rigidity and lower stress, and the bearing cap side having slightly lower rigidity and higher stress. Also, the side opposite the direction of applied load can be considered to be subjected to compressive stress. The maximum stress would exist at a position $\pm 90^\circ$ from the load, but since the joint face is at this position, the point of maximum stress is shifted slightly. When the direction of the applied load is slightly moved to the right or the left of a perfectly vertical applied load, the stress distribution is also slightly altered.

The degree of this change depends on the rigidity of each area.

When inspecting the calibration curves with the above points in mind, there is nearly a left-right symmetry in the range from 0° to 180°, while the journal block and bearing cap rigidity differences can also be seen. Thus the results can be judged as qualitatively appropriate.

2.6 Measurement Methods

2.6.1 Measurement Conditions

Engine excitation force measurements were performed with the engine load absorbed by a dynamometer. The conditions for the tests are shown in Table 3.

Table 3 Measuring conditions

Engine speed range	1600 to 6000 rpm
Dynamometer torque	Wide open throttle 40 Nm While motoring
Lubricant temperature	85 °C to 95 °C
Coolant temperature	82 °C

2.6.2 Data Sampling Method

Multi-point simultaneous sampling was given the highest priority when obtaining data. The data was processed with the results used in this method shown in Fig. 10.

During engine operation, the pulse (at top dead center)

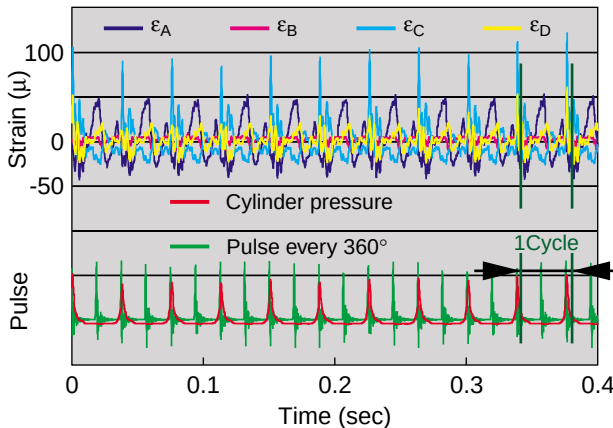


Fig. 10 Pulse examples under running conditions (wide open throttle 4000rpm)

and the cylinder pressure were measured by a revolution pulse sensor. Using the 360° pulse immediately prior to the peak cylinder pressure as start of a cycle, and the next 360° pulse immediately prior to the peak cylinder pressure as the end of the cycle, the crankshaft has rotated by an absolute angle of 720°. The sampled data are expressed as the average of 5 or more cycles.

2.7 Excitation Force Calculations

When the load direction is changed based on considerations of the tendencies for right-left symmetry and the vertical asymmetry of the strain distribution for the vertical load shown in Fig. 9, and when the output changes of each strain gauge are considered, the direction of the excitation forces can be determined if strain data is obtained from at least four locations.

The actual measurement data vectors from the four places on each main bearing journal are ϵ_A , ϵ_B , ϵ_C , and ϵ_D . These are determined, in the same way, from the strain calibration tests. As calibration load direction θ_k , magnitude $\lambda_k(\theta_k)$, and the strain ϵ_x ($x = A \sim D$) of the said locations can all be determined from the calibration tests, the sensitivity calibration value vectors, $K_A(\theta)$, $K_B(\theta)$, $K_C(\theta)$, and $K_D(\theta)$, are determined in the following way.

$$K_x(\theta_k) = \frac{\epsilon_x}{\lambda_k(\theta_k)} \quad \text{Eq. (1)}$$

The main bearing journal strain ϵ_x can be determined in the following way, using sensitivity calibration value vectors ($x = A \sim D$).

$$\epsilon_x = \lambda(\theta) \cdot K_x(\theta) \quad \text{Eq. (2)}$$

The main bearing journal strain relative error function $E(\theta)$ is obtained from the above.

$$E(\theta) = \sum_{x=A}^D \{\epsilon_x - \lambda(\theta) \cdot K_x(\theta)\}^2 \quad \text{Eq. (3)}$$

According to this measuring method, the $\lambda(\theta)$ and θ that minimize the relative error function $E(\theta)$ are determined and used as the excitation force and direction.

In Eq.(3), assuming that the q is fixed, the $l(\theta)$ resulting in a minimum $E(\theta)$ can be expressed in Eq.(4), below.

$$\lambda(\theta) = \frac{\sum_{x=A}^D \epsilon_x \cdot K_x(\theta)}{\sum_{x=A}^D K_x^2(\theta)} \quad \text{Eq. (4)}$$

In Eq.(4), the $\lambda(\theta)$ was calculated for θ throughout the range from 0° to 359° for ϵ_A to ϵ_D to determine the θ_0 where $E(\theta)$ is at a minimum as well as the corresponding $\lambda(\theta_0)$. The magnitude of the excitation force $\lambda(\theta_0)$ and the excitation force direction θ_0 were obtained from the above calculations.

3. Measurement Results

The excitation forces determined by this method are shown in Figs. 11-13.

Fig. 11 gives the excitation force of each main bearing journal for the crankshaft angle. When the No. 1 cylinder ignition is near 0°, the No.1 and No.2 main bearing journal excitation forces are at their peaks. This indicates that the greatest excitation force for each bearing journal changes in accordance with the firing sequence (1-3-4-2).

Fig. 12 is a Lissajous figure for the direction of the generated engine excitation force. The excitation force is at an angle approximately 15° from the vertical. Considering that this was mainly caused by the downward load from the

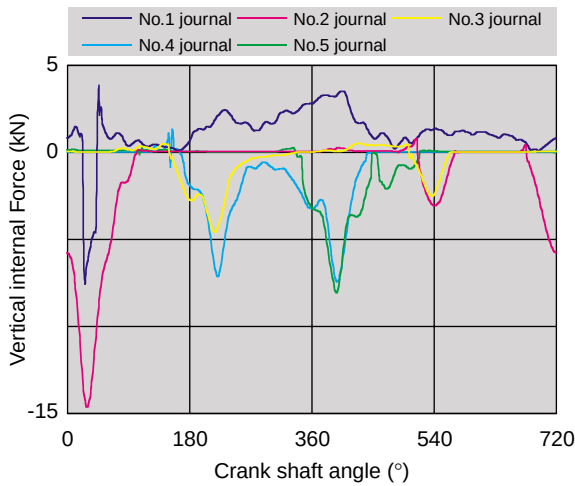


Fig. 11 Internal force at each main bearing journal (wide open throttle 1600rpm)

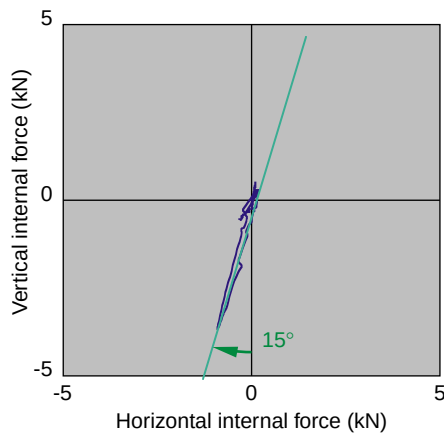


Fig. 12 Lissajous figure for internal forces

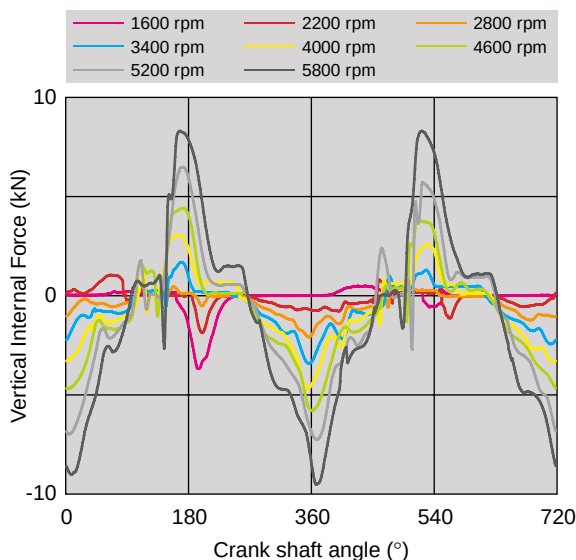


Fig. 13 Internal force variation (40Nm torque, no.3 journal)

crankshaft balance rate and that the ignition angle was set at 15° before TDC, the results seem appropriate.

Fig. 13 shows the changes in engine excitation forces that accompany increases in rpm. In the comparatively low-speed range, the effect of ignition pressure, which decreases, is large. However, in the comparatively high-speed range, we can see the significant effects from the inertia force that brings about a clearly defined peak every 180° .

The foregoing results are both non-contradictory and qualitatively appropriate. Since these results are also sufficiently linear, it is believed that accurate measurements can be made.

4. Summary

A method for directly measuring the magnitude and direction of the constantly changing excitation forces was developed. The direction and absolute value of the excitation forces were determined from the strain measurements taken during operation by multiple strain gauges attached to the internal surface of each main bearing journal. They were determined when the relative error of the strain estimated from the calibration curve was at a minimum. Measurements of the excitation forces were taken for a Civic 4-cylinder engine in the speed range of 1,600 rpm to 6,000 rpm. Consistently non-contradictory and appropriate results were obtained. This measurement method for determining excitation forces can be carried out without using large-scale measuring equipment, unlike the conventional indirect methods, making it relatively simple to measure the excitation forces.

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