Error Control and Compensation for CMM Inspection of Large-Bore Diesel Engine Blocks

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Abstract: The dimensional inspection of large-bore diesel engine blocks is highly sensitive to thermal gradients, stylus deflection, fixturing, and surface texture due to their massive size and complex geometry. To address this, we present a shop-floor error control procedure combining temperature stabilization, dynamic probe qualification, three-point free support, and 50 UPR Gaussian low-pass filtering. Comparative measurements on four production blocks validated the approach: combined temperature and probe control reduced the main bearing bore coaxiality from 0.041-0.055 mm to 0.019-0.031 mm; three-point support improved the main mating surface flatness from 0.062-0.095 mm to 0.028-0.052 mm; and 50 UPR filtering decreased cylinder bore cylindricity from 0.032-0.038 mm to 0.011-0.014 mm. These results demonstrate that optimizing measurement environments and boundary conditions significantly mitigates multiple error sources and enhances inspection consistency. Task-specific uncertainty evaluation is also discussed.

Keywords: Large-Bore Diesel Engine Block; Coordinate Measuring Machine; Error Compensation; Coaxiality; Flatness; Cylindricity

1. Introduction

The diesel engine block is the main load-bearing and enclosing component of an engine. It contains the main bearing bores, cylinder bores, camshaft bores, and internal fluid passages and is therefore a typical large, heavy, and complex box-type component. The coaxiality of the main bearing bore train, the cylindricity of the cylinder bores, and the flatness of the main mating surfaces directly affect assembly accuracy, wear of moving parts, and sealing performance. Accurate and repeatable dimensional inspection is therefore essential for process control and quality assessment in diesel engine manufacturing.

Coordinate measuring machines (CMMs) are widely used for the final inspection of engine blocks because of their three-dimensional measurement capability and extensive geometric evaluation capabilities. CMM acceptance and periodic verification are typically performed in accordance with established metrological protocols. However, large-bore engine blocks are difficult to inspect because of their large size, high mass, and deep bores. Thermal gradients, stylus deflection, fixturing-induced deformation, and surface texture can all influence the measurement result. The superposition of these effects induces measurement deviations that compromise conformity assessment.

Previous studies have addressed these error sources mainly in isolation. Thermal errors in machine tools and CMMs have been widely investigated[1], and probe pretravel and dynamic errors have been modeled and compensated[2]. Fixture-induced workpiece deformation has been studied using finite element and contact models[3, 4]. Gaussian filtering and form error evaluation have also been standardized and analyzed[5], while task-specific uncertainty and conformity assessment remain challenging[6,7]. Nevertheless, shop-floor studies that combine thermal control, probe qualification, workpiece support, and data evaluation for large engine blocks are still limited. This paper presents a practical procedure for large-bore diesel engine blocks and evaluates its effect through comparative measurements on blocks from the same production batch[7-10].



Figure 1. CMM Inspection Setup for a Large-Bore Diesel Engine Block.

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2. Measurement Methodology and Experimental Design

The CMM inspection of large-bore engine blocks requires simultaneous control of the environment, the measuring system, and the workpiece state. The procedure developed in this study includes four parts: temperature control, probe qualification, workpiece support, and data evaluation. Comparative measurements were performed on blocks from the same batch to assess the effect of the proposed measures.

2.1 Temperature Control and Thermal Deformation Suppression

Engine blocks are usually made of cast iron and have large mass and volume. Temperature variation causes thermal expansion or contraction, and a temperature difference between the surface and the interior can induce additional thermal bending. Both effects influence flatness and coaxiality evaluations. Before measurement, each block was kept in a temperature-controlled room at 20°C for at least 24h to allow the internal and surface temperatures to approach equilibrium. The room temperature was controlled at 20±1°C, and the temporal fluctuation was kept below 0.5°C/h.

Temperature sensors were attached to the block surface, and the measurement software compensated dimensional readings using the thermal expansion coefficient of cast iron. It should be noted that temperature compensation mainly corrects the proportional change in dimensions with temperature; thermal bending caused by temperature gradients must still be controlled by adequate stabilization and a stable ambient temperature.

2.2 Probe Force Analysis and Dynamic Qualification

The main bearing bores of a diesel engine block are typical deep-hole features, and long stylus extensions are required for their inspection. When the probe tip contacts the workpiece, the stylus may deflect elastically, and a touch-trigger probe also exhibits pretravel. These effects cause a deviation between the recorded coordinates and the actual contact position, and the deviation increases with stylus length.

To reduce the effects of stylus deflection and pretravel, the probe was dynamically qualified on a reference sphere before measurement. The qualification was performed with the actual stylus length, tip diameter, probe orientation, and scanning speed, and the effective tip radius, pretravel, and repeatability were determined. During measurement, the probe was advanced as close as possible to the surface normal to reduce lateral loading. For deep-hole features, the stylus length and probing direction were selected to limit deflection, and the corresponding probe compensation parameters were applied in the measurement program. Probe performance was verified in accordance with the relevant parts of ISO 10360[9, 10].

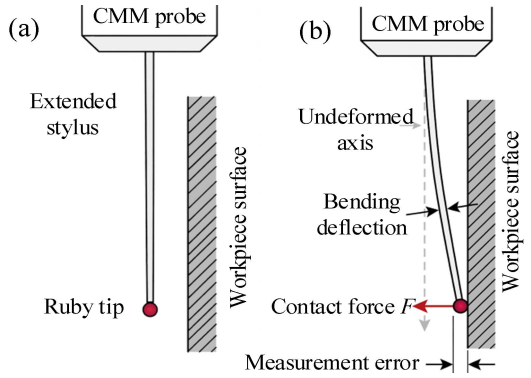

Figure 2. Schematic of Stylus Deflection and Measurement Error: (a) Before Contact; (b) After Contact.

2.3 Workpiece Support and Fixturing

Because an engine block has a high mass, the support condition on the CMM table directly affects the stress state of the workpiece. Conventional rigid clamping can introduce additional clamping stresses and cause elastic deformation of long-span mating surfaces, thereby affecting flatness evaluation.

To reduce clamping stress, a three-point free support was used. Three support pads were placed at suitable positions with high local stiffness on the bottom of the block, allowing the block to rest stably under its own weight. Low-stiffness lateral stops were used to prevent sliding without applying additional clamping force. Compared with rigid clamping, three-point free support reduces external constraint and brings the measurement state closer to the free state of the workpiece. The block was allowed to stabilize on the supports before coordinate system establishment and data acquisition. The influence of fixture-workpiece contact and compliance on workpiece deformation has been discussed in previous studies.

2.4 Coordinate System Establishment and Data Filtering

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Prior to measurement, the workpiece coordinate system was aligned with the specified design datums (surfaces and bores). To minimize alignment errors for large blocks, multiple points were sampled on the datums for iterative fitting.

Machined surfaces contain tool marks and micro-scale roughness. If all surface details are directly included in the form error evaluation, the evaluated flatness and cylindricity may be overestimated. Therefore, the raw scanned data were processed with a Gaussian low-pass filter at a cutoff of 50 UPR to suppress the influence of surface texture. The filter parameters were selected according to the drawing requirements and the measurement software specification, and the raw data were retained. Flatness and cylindricity were evaluated with reference to ISO 12781-1 and ISO 12180-1 [11, 12]. High-definition metrology provides a useful framework for form error evaluation. Filtering is an evaluation procedure rather than a physical compensation of the measuring system; therefore, both unfiltered and filtered results should be recorded.

3. Results and Analysis

The proposed procedure was applied to the inspection of a large-bore diesel engine block. The measurement results obtained before and after implementing the control measures were compared to evaluate their effects on coaxiality, flatness, and cylindricity.

3.1 Effect of Temperature and Probe Compensation on Coaxiality

The coaxiality of the crankshaft main bearing bores is an important indicator of block machining quality. Because the bearing bore train is long and deep, the measurement is sensitive to stylus deflection and thermal deformation. Four blocks from the same production batch were measured under two conditions: conventional measurement and combined compensation, where the latter included temperature stabilization at 20 °C and dynamic probe qualification. The results are listed in Table 1.

As shown in Table 1, the coaxiality values obtained under conventional measurement ranged from 0.041 to 0.055 mm, all exceeding the φ0.040 mm drawing tolerance. After temperature control and dynamic probe qualification, the values decreased to 0.019-0.031 mm, with an average reduction of approximately 0.023 mm, and all values fell within the tolerance zone. These results indicate that, under the conditions of this study, improving the thermal environment and qualifying the probe can reduce systematic deviations in deep-hole measurement and improve the consistency of coaxiality evaluation. According to ISO 14253-1, conformity assessment should also consider measurement uncertainty. Because the temperature and probe conditions were changed simultaneously, the results represent the combined effect of the two measures; separating their individual contributions requires a factorial experimental design.

3.2 Effect of Support Condition on Flatness

The flatness of the top surface, oil-pan mating surface, and gear-case mating surface directly affects assembly sealing. To evaluate the effect of the support condition, the same block was measured under conventional rigid clamping and three-point free support. The results are listed in Table 2.

As detailed in Table 2, flatness deviations under rigid clamping ranged from 0.062 to 0.095 mm, uniformly exceeding specified design tolerances. Implementing a three-point free support configuration reduced these deviations to 0.028–0.052 mm, bringing all measurements within their respective tolerance limits. This demonstrates that boundary support conditions significantly influence the evaluated flatness of large-span mating interfaces, and that a three-point free support effectively mitigates elastic deformation induced by clamping stress. Given that absolute deviations still varied across the evaluated surfaces, it is imperative that the metrological support scheme strictly replicates the free state or the operational boundary conditions specified in the engineering drawings.

Table 1. Comparison of Coaxiality Measurement Results for the Crankshaft Main Bearing Bores (mm)

Batch	Tolerance/mm	Conventional	Compensated	Difference Δ/mm
Block-01	φ0.040	0.052	0.028	0.024
Block-02	φ0.040	0.048	0.025	0.023
Block-03	φ0.040	0.055	0.031	0.024
Block-04	φ0.040	0.041	0.019	0.022

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Table 2. Comparison of Flatness of the Main Mating Surfaces Under Different Support Conditions (mm)

Surface	Tolerance/mm	Rigid clamping	Three-point support	Diff./mm
Top surface (left)	0.050	0.068	0.032	0.036
Top surface (right)	0.050	0.071	0.035	0.036
Oil-pan mating surface	0.080	0.095	0.052	0.043
Gear-case mating surface	0.050	0.062	0.028	0.034

Table 3. Comparison of Cylindricity Evaluation Results Before and After Filtering (mm)

Cylinder	Tolerance/mm	Unfiltered	50 UPR filtered	Relative change/%
1	0.020	0.035	0.012	65.7%
2	0.020	0.038	0.014	63.1%
3	0.020	0.032	0.011	65.6%
4	0.020	0.036	0.013	63.8%

3.3 Effect of Filtering on Cylindricity Evaluation

The cylinder bores are honed, and their surfaces contain micro-scale texture. During continuous scanning, high-frequency undulations may be included in the cylindricity evaluation. To analyze the effect of filtering, the same raw scan data were evaluated both without filtering and with 50 UPR Gaussian filtering. The results are listed in Table 3.

As shown in Table 3, the unfiltered cylindricity values ranged from 0.032 to 0.038 mm. After 50 UPR Gaussian filtering, the values decreased to 0.011-0.014 mm, with relative changes of 63.1%-65.7%. This indicates that filtering can suppress the influence of surface texture on cylindricity evaluation and make the result more representative of the macro-scale form. However, the filter parameters should be selected within the range permitted by the drawing or standard, and the raw data should be retained. Both unfiltered and filtered results should be reported; the filtered result should not be used to replace an original out-of-tolerance conclusion.

3.4 Feedback of Measurement Data to the Machining Process

When the measurement system is under control, a stable and repeatable position deviation observed in a production batch can be investigated together with the machine thermal state, fixture wear, and tool wear, and the results can be used to adjust tool offsets. It should be emphasized that measurement data alone cannot identify the source of the deviation. In practice, machining records, equipment status, and batch quality data should also be considered so that inspection results can support process optimization more effectively.

4. Conclusions

To address the influence of temperature, probe condition, fixturing, and surface morphology on CMM inspection of large-bore diesel engine blocks, this paper proposed an error control and compensation procedure consisting of temperature stabilization, dynamic probe qualification, three-point free support, and data filtering. Field comparison measurements were performed, and the main conclusions are as follows.

(1) After temperature stabilization at 20 °C and dynamic probe qualification, the coaxiality of the main bearing bores decreased from 0.041-0.055 mm to 0.019-0.031 mm, with an average reduction of approximately 0.023 mm. The consistency of the measurement results and the stability of conformity assessment were improved.

(2) With three-point free support, the flatness of the main mating surfaces decreased from 0.062-0.095 mm to 0.028-0.052 mm, indicating that reducing clamping constraint helps decrease additional deformation of long-span mating surfaces.

(3) After 50 UPR Gaussian filtering, the cylindricity of the cylinder bores decreased from 0.032-0.038 mm to 0.011-0.014 mm, with relative changes of 63.1%-65.7%. Filtering reduces the influence of surface texture on form error evaluation, but it should be applied within the range permitted by the drawing or standard.

The proposed procedure provides a practical reference for the CMM inspection of similar large box-type components. Owing to field constraints, the sample size was limited, and temperature control and probe qualification were implemented as a combined measure. Future work should include multi-factor experiments, repeated measurements, and a complete task-specific

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uncertainty evaluation.

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