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ORIGINAL ARTICLE

The quality control method for remanufacturing assembly based on the Jacobian-torsor model

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Abstract To improve the assembly accuracy of remanufactured parts with multiple heterogeneity and properties, and to guarantee the quality of remanufacturing product no worse than the original one, this paper takes the air tightness of remanufactured engines' cylinder block and head as the research target and proposes a quality control method based on the Jacobian-torsor model for remanufacturing assembly. First of all, three different Jacobian-torsor models for assembly tolerance are structured, and according to that, the defined torsor difference (ΔFR) of remanufacturing products is calculated by considering the geometric error of remanufactured related parts assembly influenced by the temperature field and force field. Then, the optimal tightening torque of cylinder heads' main bolts corresponding to ΔFR is achieved by applying the bivariate Lagrange interpolation method. Finally, taking the assembly of remanufactured engines' cylinder block and head as a case study to verify the proposed methods is feasible and effective.

Keywords Remanufacturing · Jacobian-torsor · Quality control of assembly · Tightening torque

1 Introduction

Nowadays, the global resource depletion and environmental contamination urge us to reflect on the traditional industrial development mode. Remanufacturing which provides a fundamental meaning to build a source-saving as well as an environment-friendly society is the key technology for implementing the circular mode of production in the industrial field [1]. Unfortunately, there are some problems in remanufacturing industry development, such as product quality and service safety [2].

The industrial practices in recent years, such as remanufacturing and refurbishing, have indicated that end-of-use products may contain significant economic value [3]. In 2013, the output value of remanufacturing is worth more than $130 billion. The remanufactured field involves the automobile industry, engineering mechanical industry, et al. In particular, the automobile industry and engineering mechanical industry account to above two thirds of the market. It is well known that the remanufactured engine is the most valuable component in the remanufacturing market. Nevertheless, so far, the quality and performance of remanufactured engines are unsatisfactory. Furthermore, the assembly quality of engines' cylinder block and head greatly influences the whole quality of remanufactured engines.

Since the twenty-first century, along with the further development of the remanufacturing industry, the research literatures of quality control for the remanufacturing assembly begin to increase. These literatures mainly focus on two different fields as follows:

1. Remanufacturing quality management. The researches of remanufacturing quality management are mainly about tolerance design, product lifecycle, and online quality control. For example, Ferguson et al. study the value of quality classification of the remanufacturing assembly process and obtain the optimal solution by a heuristic greedy algorithm [4]. Zhou et al. study the quality evaluation model to quantify the reusability of recycled wheel loaders' parts based on the fuzzy analytic hierarchy process [5]. Based on a comprehensive consideration of the

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product cost and performance, Niu et al. propose an optimization mathematical model for tolerance design of remanufacturing [6]. Cheng et al. realize continuous improvement for the quality of remanufacturing products based on product multi-lifecycle (PMLC) [7]. Considering the uncertainty of the parts' quality, Tang et al. calculate the reprocessing time of remanufactured parts by a numerical approximate analysis algorithm [8]. Ge et al. study an online quality control for the assembly process of remanufactured engines' cylinder block and head under uncertainty [9].

2. Remanufacturing assembly strategy. The research of remanufacturing assembly strategy mainly focuses on selection methods for remanufactured parts with different quality grades. For example, considering the uncertainty of recycling parts' quality and the variety of product reorganization, Jin et al. study an optimal policy for reassembly of modular products [10]. On the basis of different quality levels of recycling parts, Liu et al. study a tolerance grading allocation method for the remanufactured parts assembly [11]. Zhang et al. put forward a selective assembly for different qualities of remanufactured parts based on the tolerance design and surface engineering technique [12]. Considering the core recycled parts with different quality levels, Cai et al. study the optimal acquisition and production policy in a hybrid manufacturing/remanufacturing system [13]. Su et al. study the buffer allocation of a hybrid manufacturing/remanufacturing system based on the quality grading of parts [14]. To improve the assembly accuracy and to minimize the cost of remanufacturing products, Liu et al. study several reassembly methods for the remanufactured parts with different accuracies [15].

While the prior researches above provide great support for improving the assembly quality of remanufacturing products, there are few literatures about the quality control methods for the remanufacturing assembly process of remanufactured parts which have multiple heterogeneity and properties under the influence of two fields—temperature field and force field (substituting by multiple fields for short in the following sections).

How to make the quality of the remanufacturing products satisfy the standard requirement effectively and feasibly is a considerable controversy in remanufacturing engineering. In this paper, we study the assembly process of remanufactured engines' cylinder block and head, propose three Jacobian-torsor models to calculate the assembly tolerance of three different general assembly cases, and define the torsor difference (ΔFR). Given these results, the mathematical relation between the tightening torque of cylinder heads' main bolts and the torsor difference is explored by the bivariate Lagrange interpolation method. Finally, a case study verifies that the air tightness of remanufactured engines' cylinder block can be guaranteed through adjusting the optimal range value of tightening torque of cylinder heads' main bolts. Overall, this paper provides a new theory and method to guarantee the quality of remanufacturing products.

2 Jacobian-torsor model

2.1 Assembly analysis based on the Jacobian-torsor model

The torsor is applied to represent the position and orientation of a surface in relation to another surface with a kinematic way in tolerance analysis [16]. In the case of general assembly of products, every part and component of the structure, named functional elements, would produce imperceptible assembly errors because of the parts' change in several factors, such as size, position, and shape. These assembly errors can be expressed by torsors S in spatial six degrees of freedom. Equation (1) is the expression of S. Finally, these small assembly errors of functional elements in spatial six degrees of freedom would be developed gradually into general assembly errors through the transmission of the assembly dimension chain.

$$S = \begin{bmatrix} \delta_\mu & \delta_\nu & \delta_\omega & \delta_\alpha & \delta_\beta & \delta_\gamma \end{bmatrix}^T \tag{1}$$

where δ_μ, δ_ν, and δ_ω represent translational vectors of assembly parts on the axes x, y, and z in spatial coordinate system with a random point as origin. Likewise, δ_α, δ_β, and δ_γ are three specific rotational vectors of assembly parts rounding the axes x, y, and z. All of these elements in Eq. (1) can be computed by finite element or mechanical calculation methods.

During a practical working situation, there are several geometric errors and dimensional changes in parts and components when original products and remanufacturing products are influenced by multiple fields. Furthermore, the force field could induce geometric errors and dimensional changes of assembly parts in size, direction, and magnitude in spatial six degrees of freedom. Thereby, the translational vectors and rotational vectors are used to represent the assembly tolerance effectively. Meanwhile, the geometric errors caused by the temperature load are usually regarded as a scaling factor, because there is no direction change of geometric errors in spatial six degrees of freedom, and the magnitude change of geometric errors will increase or decrease according to a certain proportion. However, the repaired coating layer of remanufactured parts has multiple heterogeneity and properties; thus, the remanufactured parts will also have a certain direction change of geometric errors caused by the deformation of the repaired coating layer under the influence of the temperature field. Both the force field and temperature field affect the physical properties of remanufactured parts, and the assembly tolerance caused by geometric errors can be computed according to Eq. (1).

In conclusion, considering the influence factors for assembly parts and general assembly, the assembly Jacobian-torsor model (AJT model) for original products is constructed according to the size change, location change, and shape change in assembly parts. Furthermore, the manufacturing assembly Jacobian-torsor model (MAJT model) for original products and the remanufacturing assembly Jacobian-torsor model (RMAJT model) for remanufacturing products are proposed by modifying the AJT model with consideration of the different degrees of geometric error in assembly parts under the influence of multiple fields respectively (Fig. 1).

2.2 Tolerance modeling based on the Jacobian-torsor model

Desrochers and Laperriere use the rigid body kinematics method to analyze the tolerance and construct the torsor model and Jacobian method which are respectively suitable to the tolerance representation and propagation. They combine the advantages of these two methods and put forward the unified Jacobian-torsor model. In this paper, we construct the Jacobian-torsor model and analyze the assembly tolerance by the interval arithmetic, where the small displacements of parts are presented by point sets and the variables in space are expressed by torsors. Equation (2) is the basic expression of the Jacobian-torsor model, in which functional requirement [FR] for general assembly is related to the functional elements [FE] for assembly parts mathematically and such geometrical relationship could be described by a Jacobian matrix [J] [17].

$$[\mathrm{FR}] = [J][\mathrm{FE}] = \left[[J]_{\mathrm{FE}_1}\cdots[J]_{\mathrm{FE}_n}\right] \times \left[\begin{bmatrix}[\underline{\mu},\overline{\mu}]\\ [\underline{\nu},\overline{\nu}]\\ [\underline{\omega},\overline{\omega}]\\ [\underline{\alpha},\overline{\alpha}]\\ [\underline{\beta},\overline{\beta}]\\ [\underline{\gamma},\overline{\gamma}]\end{bmatrix}_{\mathrm{FE}_1} \cdots \begin{bmatrix}[\underline{\mu},\overline{\mu}]\\ [\underline{\nu},\overline{\nu}]\\ [\underline{\omega},\overline{\omega}]\\ [\underline{\alpha},\overline{\alpha}]\\ [\underline{\beta},\overline{\beta}]\\ [\underline{\gamma},\overline{\gamma}]\end{bmatrix}_{\mathrm{FE}_n}\right]^T \quad (2)$$

where the functional requirement [FR] is the translational and rotational vectors of general assembly. $[\mathrm{FR}] = \left[[\underline{\mu},\overline{\mu}], [\underline{\nu},\overline{\nu}], [\underline{\omega},\overline{\omega}], [\underline{\alpha},\overline{\alpha}], [\underline{\beta},\overline{\beta}], [\underline{\gamma},\overline{\gamma}]\right]^T_{\mathrm{FR}} \cdot \left(\underline{\mu},\underline{\nu},\underline{\omega},\underline{\alpha},\underline{\beta},\underline{\gamma}\right)$ and $\left(\overline{\mu},\overline{\nu},\overline{\omega},\overline{\alpha},\overline{\beta},\overline{\gamma}\right)$ are lower limits and upper limits of the tolerance intervals respectively.

$[\mathrm{FE}]_{\mathrm{FE}_i} = \left[[\underline{\mu},\overline{\mu}], [\underline{\nu},\overline{\nu}], [\underline{\omega},\overline{\omega}], [\underline{\alpha},\overline{\alpha}], [\underline{\beta},\overline{\beta}], [\underline{\gamma},\overline{\gamma}]\right]^T_{\mathrm{FR}}$
Functional elements [FE] represent the geometric tolerance of a single part and the assembly tolerance of related parts.

$[J] = \left[[J]_{\mathrm{FE}_1}[J]_{\mathrm{FE}_2}\cdots[J]_{\mathrm{FE}_{n-1}}[J]_{\mathrm{FE}_n}\right]$ is the Jacobian matrix which describes the relationship between vector [FR] and vector [FE]. n represents the number of functional elements on the tolerance transport chain.

The Jacobian matrix can be expressed as

$$[J]_{\mathrm{FE}_i} = [J]_0^i = \begin{bmatrix}[R_0^i]_{3\times3} & \cdots & [W_i^n]_{3\times3}\cdot\left([R_0^i]_{3\times3}\cdot[R_{\mathrm{PT}_i}]_{3\times3}\right)\\ \vdots & \ddots & \vdots\\ [0]_{3\times3} & \cdots & [R_0^i]_{3\times3}\cdot[R_{\mathrm{PT}_i}]_{3\times3}\end{bmatrix}_{6\times6} \quad (3)$$

where $[R_0^i]=[C_{1i}C_{2i}C_{3i}]$. $[R_0^i]$ is the local orientation change of frame i with respect to frame 0. C_{1i}, C_{2i},, and C_{3i} are the orientation vectors of axes x_i, y_i, and z_i on frame 0. $[R_{\mathrm{PT}i}] = [C_1C_2C_3]_{\mathrm{PT}_i}$. $[R_{\mathrm{PT}i}]$ describes the direction change of tolerance with respect to the three coordinate axes of frame i. C_1, C_2, and C_3, correlated to $[\mathrm{FE}_i]$ and $[R_{\mathrm{PT}i}]$, are the orientation vector of tolerance on frame i.

$$\left[W_i^n\right] = \begin{bmatrix}0 & -dz_i^n & dy_i^n\\ dz_i^n & 0 & -dx_i^n\\ -dy_i^n & dx_i^n & 0\end{bmatrix}$$

where $[W_i^n]$, a matrix composed of vectors $[d_n-d_i]$, indicates the position change on frame n with respect to frame i. d_i indicates the position vector of the origin of reference frame i on 0. $dx_i^n=dx_n-dx_i, \cdot dy_i^n=dy_n-dy_i$ and $dx_i^n=dz_n-dz_i$.

[FE] of Eq. (2) can be calculated as follows:

$$[\mathrm{FE}]_{\mathrm{FE}_i} = [R_{\mathrm{PT}_i}]^{-1}\cdot[T] \quad (4)$$

where [T] is the tolerance torsor based on [FE], which can be calculated with consideration of the geometric tolerance of a single part and the assembly tolerance of related parts. The tolerance zones and associated torsor parameters table can be consulted [18].

In reality, compared to the case not influenced by multiple fields, there are changes of [FE] in spatial six degrees of freedom if taking multiple fields into consideration. According to Eq. (1), the function elements [FE] changes consist of translational vectors in the coordinate system and rotational vectors rounding the coordinate system, which can be covered as follows:

$$S = \left[\ \delta_{\mu_i} \quad \delta_{\nu_i} \quad \delta_{\omega_i} \quad \delta_{\alpha_i} \quad \delta_{\beta_i} \quad \delta_{\gamma_i}\ \right]^T \quad (5)$$

where $\delta_{\mu i}$, $\delta_{\nu i}$, and $\delta_{\omega i}$ are three translational vectors of the origin of the coordinate system on axes x, y, and z. Likewise, δ_α, δ_β, and δ_γ are three specific rotational vectors around the axes.

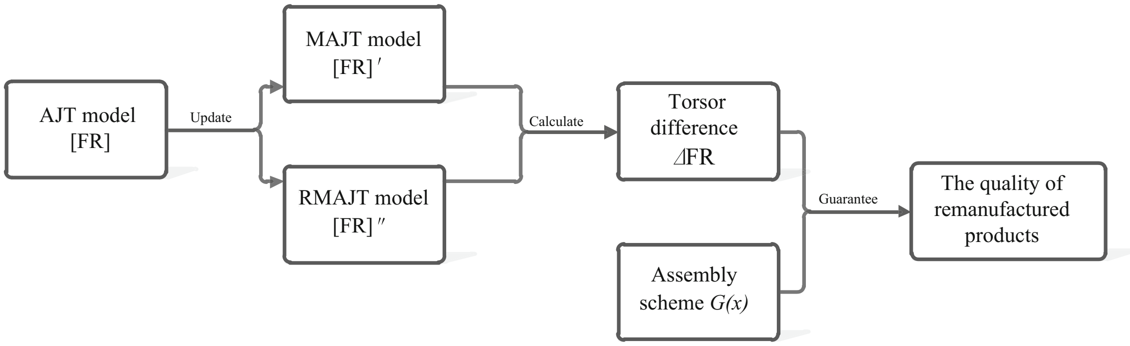


Fig. 1 The flowchart of the quality control method for the remanufacturing assembly

The variables in Eq. (3) will be updated after changes of [FE]:

$$[R_0^i] = [C_{1i}C_{2i}C_{3i}]\cdot[C_x]\cdot[C_y]\cdot[C_z]$$

where $[C_x]$ is the transition matrix which rotates $\Delta\alpha_i$ around the x-axis on frame i.

$$[C_x] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Delta\alpha_i & -\sin\Delta\alpha \\ 0 & \sin\Delta\alpha_i & \cos\Delta\alpha_i \end{bmatrix}$$

where $[C_y]$ is the transition matrix which rotates $\Delta\beta_i$ around the y-axis on frame i.

$$[C_y] = \begin{bmatrix} \cos\Delta\beta_i & 0 & \sin\Delta\beta_i \\ 0 & 1 & 0 \\ -\sin\Delta\beta_i & 0 & \cos\Delta\beta_i \end{bmatrix}$$

where $[C_z]$ is the transition matrix which rotates $\Delta\gamma_i$ around the z-axis on frame i.

$$[C_z] = \begin{bmatrix} \cos\Delta\gamma_i & -\sin\Delta\lambda_i & 0 \\ \sin\Delta\gamma_i & \cos\Delta\gamma_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

As a result, dx_i^n, dy_i^n, and dz_i^n update into $dx_i^n=dx_n-dx_i+\Delta\mu_i$,, $dy_i^n=dy_n-dy_i+\Delta v_i$, and $dzn_i^n=dz_n-dz_i+\Delta\omega_i$

Substituting , and $[R_{\mathrm{PT}i}]$ in the above equations, and rewriting Eq. (3), the $[J]$ of MJT is obtained. According to Eq. (2), we have the MJT matrix [FR]′ affected by multiple fields after calculation of [FE] by Eq. (4) and $[J]$ of MJT.

2.3 The torsor difference of remanufacturing products

Because of the multiple heterogeneity and properties of remanufactured parts, the repaired coating layer will have a certain physical deformation under the influence of multiple fields. We can get Eq. (6) associated with the changes of [FE].

$$S = \begin{bmatrix} \delta_{\mu_i}+\Delta\delta_{\mu_i} & \delta_{\nu_i}+\Delta\delta_{\nu_i} & \delta_{\omega_i}+\Delta\delta_{\omega_i} & \delta_{\alpha_i}+\Delta\delta_{\alpha_i} & \delta_{\beta_i}+\Delta\delta_{\beta_i} & \delta_{\gamma_i}+\Delta\delta_{\gamma_i} \end{bmatrix}^T \quad (6)$$

where $\Delta\delta_{\mu_i}$, $\Delta\delta_{\nu_i}$, and $\Delta\delta_{\omega_i}$ represent the translational vector changes of remanufactured parts (given by Eq. (5)) affected by the multiple fields. Likewise, $\Delta\delta_{\alpha_i}$, $\Delta\delta_{\beta_i}$, and $\Delta\delta_{\gamma_i}$ represent the specific rotational vector changes. According to the methods mentioned in Section 2.2, the RMAJT matrix [FR]″ is calculated after modifying the AJT model on account of the geometric errors in assembly parts.

The torsor difference ΔFR of the remanufacturing product represents the difference between the MJT matrix [FR]′ and RMAJT matrix [FR]″, which can be calculated as follows:

$$\Delta\mathrm{FR} = [\mathrm{FR}]'' - [\mathrm{FR}]' \quad (7)$$

$$\Delta\mathrm{FR} = [\mathrm{FR}]' - [\mathrm{FR}]'' \quad (8)$$

The remanufactured cylinder block and head will have a certain physical deformation in the convex point or concave point under the influence of multiple fields. When the convex point affects the assembly, Eq. (7) is taken to calculate the torsor difference. Otherwise, Eq. (8) is applied to the case of the concave point. From ΔFR, the assembly quality of remanufacturing products with multiple heterogeneity and properties is guaranteed through a modified assembly scheme $G(x)$, and then the influence of assembly errors is reduced.

Taking the assembly of remanufactured diesel engines' cylinder block and head as an example, the range of translational vectors of assembly tolerance on the x-axis and y-axis arisen from ΔFR can be controlled by kinds of normal sealing technologies, while the effect of ΔFR on the z-axis is serious and thus the effect on the air tightness of remanufactured diesel engines' cylinder block and head cannot be ignored. The optimal tightening torque of main bolts of the cylinder head can be calculated as the modified assembly scheme $G(x)$ based on the value of ΔFR, which improves the assembly quality and guarantees the air tightness of remanufactured diesel engines' cylinder block and head.

3 Bivariate Lagrange interpolation method

In this paper, we propose a mathematical relation between the torsor difference and tightening torque by an analogous analysis for the inputs and outputs of intervals. Supposing N sets of input intervals and their corresponding N sets of output intervals, we have

$$\text{inputs}: [x_1, y_1], [x_2, y_2], [x_3, y_3] \cdots [x_N, y_N]$$

$$\text{outputs}: [\alpha_1, \beta_1], [\alpha_2, \beta_2], [\alpha_3, \beta_3] \cdots [\alpha_N, \beta_N]$$

Based on the principle that a point can be determined by the horizontal and vertical values in the two-dimensional plane, similarly, an interval can be fixed by its left and right endpoints. Therefore, we have the function between N sets of input and output intervals above as follows supposing these N sets of input intervals as N random points:

$$\begin{cases} \alpha_k = f(x_k, y_k) \\ \beta_k = g(x_r, y_r) \end{cases} \tag{9}$$

where

$$k = 1, 2 \cdots N, \cdot r = 1, 2 \cdots N$$

In practice, such function does not have closed form solutions. To solve this kind of problem, an interpolation method could be used to fit the function relationship given some monitored discrete values. In this paper, the method to fit the function updates from the unary interpolation function to the binary as there are two variables in the objective function.

Similar to the unary interpolation function, the idea of the binary is to construct a new function $U(x,y)$ to fit the original function $u(x,y)$, which is realized by submitting the observed discrete sets (x_i, y_i) into $U(x,y)$ to fit the observed function value u_{ij} for $u(x,y)$. Consequently, the function $u(x,y)$ can be fitted for linking the input intervals to output intervals. Based on many methods to solve the binary interpolation function studied by previous works, for convenience and descriptive completeness, we impose the popular bivariate Lagrange interpolation method as below:

$$\varphi_{kr}(x, y) = l_k(x) l'_k(y)$$

where

$$l_k(x) = \prod_{t=0, t\neq k}^{N} \frac{x - x_t}{x_k - x_t} \quad l'_r(y) = \prod_{t=0, t\neq r}^{N} \frac{y - y_t}{y_k - y_t}$$

Thus, if $\varphi(x,y)$ linearly independent to point sets (x_i, y_i), the interpolation polynomial would satisfy the interpolation conditions as follows:

$$\begin{cases} f'_{N,N}(x, y) = \sum_{k=1}^{N} \sum_{r=1}^{N} l_k(x)\, l'_r(y) f(x_k, y_r) \\ g'_{N,N}(x, y) = \sum_{k=1}^{N} \sum_{r=1}^{N} l_k(x) l'_r(y) g(x_k, y_r) \end{cases} \tag{10}$$

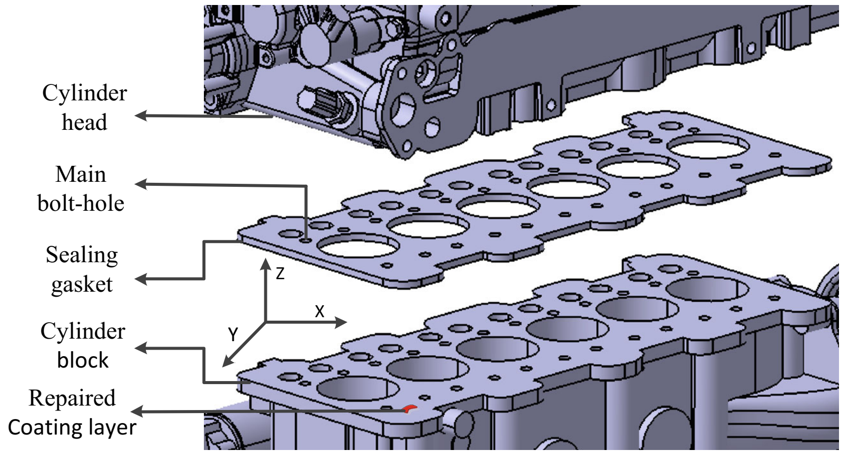
According to Eq. (10), the function of the input and output intervals is fitted.

In this paper, the interval model is proposed to describe the relationship between the tightening torque of the main bolt in $G(x)$ and the torsor difference ΔFR_z. To guarantee the air tightness of remanufactured diesel engines' cylinder block and head meets the criterion, large observations of the torsor difference and tightening torque values in the remanufactured engine, which meet the qualification standard of air tightness, are collected to fit the values of the tightening torque of the main bolt and the torsor difference ΔFR_z by the bivariate Lagrange interpolation method. By this model, we could determine the $G(x)$ with respect to the related torsor difference and control the air tightness of remanufactured diesel engines' cylinder block and head effectively

4 Case study

The remanufactured six-cylinder diesel engine is taken as an example in this case study. In general, the average standard-reaching rate of air tightness in remanufactured engines' cylinder block and head is 85 %, and such rate can be improved if we could find the influencing factors and then identify a reasonable assembly scheme. Considering the structure of a remanufactured six-cylinder diesel in this paper in which each cylinder head has only one cylinder block assembly, the Jacobian-torsor model-based is proposed to calculate the assembly tolerance of a single-cylinder. Figure 2 is the assembly drawing of a remanufactured six-cylinder diesel engine in this paper, which includes the cylinder block, cylinder head, and sealing gasket. The sealing effect of the gasket is almost the same no matter to the original engine or remanufactured one, and the assembly quality of remanufactured six-cylinder diesel engines' block and head is the key point for air tightness.

Fig. 2 The assembly drawing of the remanufactured six-cylinder diesel engine



To ensure the air tightness of remanufactured engines' cylinder block and head, the assembly tolerance should be calculated, and then the influence of the assembly error could be reduced through a reasonable modified assembly scheme.

The key functions of the engines' cylinder head are sealing and forming a combustion chamber with the piston and cylinder. Along with the operation of engines under normal working condition, the temperature of gas increases to 1800 °C and the friction occurs due to high-speed moving of related parts, thereby the physical properties of cylinder block and head would be affected [19]. Moreover, the assembly tolerance of the cylinder block and head would be influenced inevitably. In this paper, we primarily consider the influence of assembly tolerance along the *z*-axis on account of the error sensitivity and impact factors for air tightness of engines' cylinder block and head.

4.1 Calculation for the torsor difference ΔFR_z

The Jacobian-torsor equation of engines' cylinder block and head can be established as follows:

$$[\mathrm{FR}] = \left[[J]_{\mathrm{block}}[J]_{\mathrm{head}}\right]\cdot\left[[FE]_{\mathrm{block}}[FE]_{\mathrm{head}}\right]^T \tag{11}$$

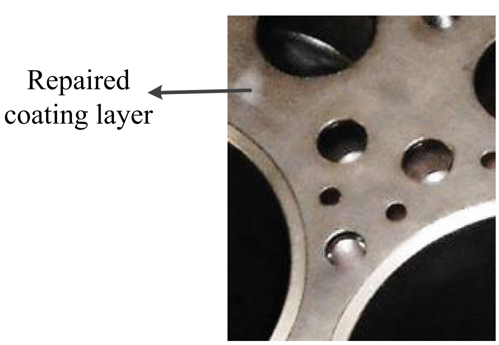


Fig. 3 The remanufactured engine's cylinder with repaired coating layer

Computing Eq. (11) by the method mentioned in Section 2, we have the AJT matrix [FR] of engines' cylinder block and head:

$$[\mathrm{FR}] = \begin{bmatrix} [-0.2083, 0.2015] \\ [-0.1895, 0.1953] \\ [-0.4847, 0.4738] \\ [0, 0] \\ [-0.0078, 0.0078] \\ [-0.0078, 0.0078] \end{bmatrix} \tag{12}$$

Equation (12) represents the assembly tolerance of engines' cylinder block and head without the influence of multiple fields. The unit is the millimeter.

Affected by multiple fields, the engines' cylinder block and head would have a certain physical deformation on their surface, and this deformation can be calculated through the finite element or mechanical calculation. Furthermore, this deformation could prompt the change of $[R_0^i]$, $[W_i^n]$, and $[R_{\mathrm{PT}_i}]$ in Eq. (3), and then have the MAJT matrix $[FR]'$ of engines' cylinder block and head:

$$[\mathrm{FR}]' = \begin{bmatrix} [-0.2352, 0.2285] \\ [-0.1962, 0.2086] \\ [-0.7738, 0.7847] \\ [0, 0] \\ [-0.0078, 0.0078] \\ [-0.0463, 0.0463] \end{bmatrix} \tag{13}$$

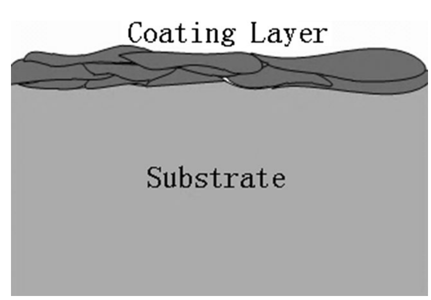


Fig. 4 Substrate and coating layer

Table 1 Partial data of torsor difference ΔFR_z and optimal tightening torque

Project	Torsor difference ΔFR_z	Optimal tightening torque T
1	[−0.0912,0.1250]	[278,282]
2	[−0.1067,0.1285]	[277,282]
3	[−0.1138,0.1299]	[274,279]
4	[−0.1149,0.1363]	[273,278]
5	[−0.1208,0.1396]	[272,276]
6	[−0.1381,0.1524]	[269,272]
7	[−0.1393,0.1447]	[268,274]
8	[−0.1435,0.1657]	[267,271]
9	[−0.1483,0.1534]	[265,272]
10	[−0.1548,0.1691]	[262,269]

In the case of remanufactured engine assembly, the quality requirements and performance requirements of remanufactured engines' cylinder block and head for the remanufactured engine assembly are no worse than those of the original parts. In particular, the coating repaired technology and thermal spraying to coat layer NiCrBSi would be applied on the damaged engines' cylinder and the advanced one, respectively (Fig. 3) is a picture of a real remanufactured engine's cylinder with a repaired coating layer..

The alloy coating layer NiCrBSi has been well recognized in the remanufactured parts restoration because of its excellent physical properties and low cost [20]. Even having such good physical properties, in practice, a repaired coating layer would be more fatigued than the whole substrate made of alloy cast iron, which induce the convex point or concave point on the coating layer under the influence of multiple fields. This paper researches the remanufactured diesel engines' cylinder block and head assembly, and a convex point on the repaired coating layer exists, as shown in Fig. 4. Considering the geometric errors arising from the convex point, we have RMAJT matrix [FR]″ of remanufactured diesel engines' cylinder block and head as follows:

$$[FR]'' = \begin{bmatrix} [-0.2579, 0.2567] \\ [-0.2584, 0.2649] \\ [-0.9193, 0.9415] \\ [0, 0] \\ [-0.0078, 0.0078] \\ [-0.0724, 0.0724] \end{bmatrix} \tag{14}$$

Comparing $[FR]''$ to $[FR]'$, we find that the assembly errors on the z-axis of $[FR]''$ and $[FR]'$ are [−0.9193,0.9415] and [−0.7738,0.7847]. Then, the value of ΔFR_z is calculated as [−0.1455,0.1568] according to Eq. (7).

4.2 Estimation for the range value of optimal tightening torque *T*

The measures should be taken to guarantee the quality of the remanufactured engine no worse than the original one. In terms of the remanufactured engine, the tightening torque of main bolts of the cylinder head would affect the air leakage of the engine block and head. In this paper, we choose the assembly of remanufactured engines in an enterprise as an example. The single-cylinder block and head assembly in remanufactured six-cylinder diesel engine has four M16 main bolts with 12.9 strength grade. Moreover, a test for the air tightness of remanufactured diesel engines' cylinder block and head is designed under 30-kPa pressure, and the results of air tightness and the general assembly would be qualified if air leakage is less than 100 ml/min. Considering both life span and tightness of main bolts, finally, the values of torsor difference ΔFR_z and the optimal tightening torque T can be obtained by accounting for the 40 sets of data of a single-cylinder block and head assembly with the standard-reaching rate of air tightness. Partial data is showed in Table 1.

In the actual working condition, if ΔFR_z falls in the interval [−0.0857,0.0961], the assembly standard of main bolts of original engines' cylinder head can be applied to the remanufactured one; if the right endpoint value of ΔFR_z is

Table 2 The comparison between the new assembly standard and the traditional assembly standard

Assembly standard	Project	1	2	3	4	5	6
Traditional assembly standard	Number	207	206	207	205	208	208
	Standard-reaching rate (%)	85.64	84.56	84.95	85.31	86.18	85.53
	Average value of air tightness (ml/min)	90.47	92.72	92.36	92.14	90.71	91.66
	Standard deviation of air tightness	1.73	1.72	1.69	1.67	1.68	1.65
New assembly standard	Number	204	205	205	207	206	208
	Standard-reaching rate (%)	89.74	90.19	89.52	89.21	90.07	89.89
	Average value of air tightness (ml/min)	88.75	88.18	89.37	90.19	89.52	89.13
	standard deviation of air tightness	1.54	1.56	1.49	1.52	1.52	1.51

greater than 1.7846, the remanufactured parts should be checked and repaired again. In this case study, the value of ΔFR_z is [−0.1455,0.1568]; hence, we use the bivariate Lagrange interpolation method to fit the 40 sets of input and output data for the single-cylinder block and head assembly by MATLAB. After that, the estimated range value of the optimal tightening torque is [267.64,271.23]; finally, the tightening torque of four main bolts in this case should be controlled in [268,271] for good.

4.3 Comparison

In this remanufactured engine enterprise, the project team analyzes six different batches of remanufactured engines produced by the new assembly standard in this paper. We find that the standard-reaching rate of air tightness of engines' cylinder and block improves from 85.36 to 89.78 % compared to that produced by traditional assembly standard, the average value of air tightness decreases from 91.67 to 89.19 ml/min, and the average standard deviation of air tightness decreased by an average of 0.17. The changes are shown in Table 2.

The implement experience of a new assembly standard to the assembly of remanufactured diesel engines' cylinder block is summarized as follows:

1. Assembling by applying the new assembly standard in this paper, the standard-reaching rate of air tightness of remanufactured diesel engines' cylinder and block is improved; hence, the whole quality of the remanufactured engine is guaranteed.
2. Along with the improvement of the standard-reaching rate of air tightness of remanufactured diesel engines' cylinder block and head, the number of unqualified cylinders which need to be checked and repaired again decreases because of the reduction in quantities of unqualified products. Moreover, the extra production costs of remanufactured engine enterprise are also saved.
3. The new assembly standard in this paper optimizes the traditional assembly standard and is suitable to the assembly of remanufactured diesel engines' cylinder and block.

5 Conclusion

In this paper, to improve the assembly accuracy of remanufactured parts with multiple heterogeneity and properties, and to guarantee the security service performance of remanufacturing products no worse than the original products, we propose a quality control method for assembly of remanufacturing products by considering the remanufactured parts under the influence of multiple fields. Moreover, the AJT model is constructed to calculate the tolerance of the general assembly in spatial six degrees of freedom. On account of the geometric errors of original products and remanufacturing products in multiple fields, the MAJT model and RMAJT model are built. Thereby, based on these two models above, we determine the torsor difference, and look for a reasonable assembly scheme to guarantee the quality of the general assembly.

Finally, this paper takes the assembly process of a remanufactured diesel engine's cylinder block and head with multiple structures and properties influenced by multiple fields as a research example. The optimal tightening torque of the main bolts of the cylinder head is determined based on the value of torsor difference, hence guaranteeing the air tightness of remanufactured diesel engine's cylinder block and head effectively.

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