Reliability analysis and optimization of turbocharger turbine of marine low speed diesel engine under complex load

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Abstract. In this paper, aiming at the reliability analysis and optimization of jth series marine low-speed diesel engine supercharger of Chongqing JIANGZENG Shipbuilding Heavy Industry Co., Ltd., a response surface mathematical model is constructed by using 62 groups of dispersive simulation analysis data to verify the accuracy and effectiveness of the mathematical model. Based on this, Monte Carlo sampling is carried out to obtain the reliability of turbine disk is 0.943, and the reliability of turbine blade is 0.96. Reliability optimization space. Based on NSGA-II multi-objective genetic algorithm, the reliability of turbine disk and turbine blade is optimized by taking the stress value and machining cost of turbine disk and turbine blade as the objective function. The reliability of turbine disk and turbine blade is 1, the stress value of turbine blade is optimized by 4.7941%, the stress value of turbine disk is optimized by 3.0136%, the machining cost of turbine blade is optimized by 15.5087%, and the machining cost of turbine disk is optimized by 3.9907%. Finally, the results of genetic algorithm and simulation analysis are compared, the difference is less than 5%, which shows that the data based on NSGA-II multi-objective genetic algorithm has practical application reference value.

1 Introduction

Marine diesel engine emission has become one of the sources of marine pollution. With the worsening of energy and environmental problems, the International Maritime Organization has formulated new international standards for marine diesel engine emission. Enterprises all over the world are committed to the research of controlling marine diesel engine emission, and constantly have stricter requirements for the performance and technical level of marine power plant [1].

Supercharger is an important part of the main marine power plant. As an important part of supercharger, turbine technology directly affects the specific power, power, economy and reliability of marine diesel engine [2]. In this paper, the structural strength of jth series marine low-speed diesel supercharger turbine under complex load is analyzed, and the response surface mathematical model is constructed based on the data of decentralized simulation. The reliability analysis is carried out by Monte Carlo sampling method, and the reliability optimization and verification are carried out based on NSGA-II multi-objective genetic algorithm. The research in this paper will provide theoretical reference for the structural design and reliability optimization of turbocharger of marine low-speed diesel engine, and have practical reference value.
2 Strength analysis of turbine structure

2.1 Pretreatment of turbine structure strength analysis

2.1.1 Turbine geometry model processing. The turbine geometry model is shown in Figure 1 (a). In order to save computing resources and time cost, the periodic simulation model is used instead of the overall geometric model for structural strength analysis, as shown in Figure 1 (b).

![Figure 1(a). Geometric model of turbine disk](image)

![Figure 1(b). Periodic simulation model of turbine disk](image)

2.1.2 Turbine material parameters. The turbocharger disk material of marine low-speed diesel engine is GH901, and the turbine blade material is K491. According to the superalloy manual [3], the material properties are determined as shown in Table 1.

| Material properties          | Material parameters (turbine blade K491) | Material parameters (turbine disk GH901) |
|-----------------------------|----------------------------------------|----------------------------------------|
| Density                     | 7750\( kg m^{-3} \)                   | 8210\( kg m^{-3} \)                   |
| Thermal expansion Coefficient | 1.388E-05\( \text{C}^{-1} \)            | 1.55E-05\( \text{C}^{-1} \)            |
| Young's modulus             | 1.67E-05\( MPa \)                     | 1.73E-05\( MPa \)                     |
| Poisson's ratio             | 0.33                                   | 0.33                                   |
| Yield Strength              | —                                      | 960\( MPa \)                           |
| Tangent modulus             | —                                      | 6553\( MPa \)                          |
| Thermal Conductivity        | 23.32\( \text{Wm}^{-1}\text{K}^{-1} \) | 22.8\( \text{Wm}^{-1}\text{K}^{-1} \) |

2.1.3 Mesh generation of turbine model. For marine low-speed diesel engine supercharger turbine, the grid is divided into two parts: the global grid size is 0.8mm, the local grid size is 0.4mm, the grid refinement area is the contact part of turbine tenon and tenon groove, the total number of nodes after grid division is 448334, the total number of grid units is 261044, and the grid division is shown in Figure 2 (a). As shown in Figure 2 (b), a large number of grid extremum values are in the range of 0.5-0.88, which shows that the quality of grid division is good.
2.2 Turbine constraints and loads

2.2.1 Service load. The complex environmental load of marine low-speed diesel engine turbocharger turbine under high temperature and high pressure includes flow field load and thermal load. The pressure distribution and temperature distribution of turbine blade are the main influencing factors in the strength analysis of turbine structure, as shown in Fig. 3 (a) is the pressure distribution of turbine blade, as shown in Fig. 3 (b) is the temperature distribution of turbine blade.

2.2.2 Working load and contact of mortise and tenon. According to the structural strength analysis of the turbocharger turbine of marine low-speed diesel engine, the complex working load under high temperature and high pressure is mainly the overall rotation speed, as shown in Figure 4 (a) is the overall rotation speed setting of the turbine. In the process of structural strength analysis, it is necessary to consider the contact position setting of tenon and tenon. In this paper, the friction contact mode is adopted, the friction coefficient of rigid body is 0.2, and the friction contact pair is the contact surface of tenon and tenon, as shown in Figure 4 (b).
2.2.3 External constraints. According to the structural strength analysis of the compressor and turbine of the marine low-speed diesel engine supercharger, the main external constraints under high temperature and high pressure are spatial constraints. As shown in Fig. 5 (a), the constraint condition of turbine space position is selected. During the structural strength analysis of periodic simulation model, the rotational symmetry constraint is selected as shown in Fig. 5 (b).

2.3 Strength analysis of turbine structure
According to the structural strength analysis of the marine low-speed diesel supercharger turbine, as shown in Figure 6 (a), the stress distribution of the turbine disk is 596.78mpa. According to the standards of China Aviation Materials Manual, when GH901 is at 600 ℃, its yield strength is 1010mpa, which shows that the strength of the turbine disk meets the material requirements under this working condition; as shown in Figure 6 (b), the stress distribution of the turbine blade The maximum value of turbine blade is 408.39mpa. According to Q / kj02.08-1995 standard, when material K491 is at 600 ℃, its yield strength is 822mpa. It can be seen that the strength of turbine blade under this condition meets the material requirements.
3 Turbine reliability analysis

3.1 Numerical simulation of turbine dispersion
The reliability of a product can be characterized by quantitative estimation of survival probability, having a specified confidence level, operating within a specified period of time, and operating under specified service conditions [4-7]. The influencing factors and data of structural strength analysis of marine low-speed diesel engine turbocharger are shown in Table 2, where -1 level represents low level, 0 level represents center level, and +1 level represents high level, and the corresponding positions of each factor are shown in Figure 7.

| Level | Root chamfer | Outer circle of turbine disk | Fillet at the bottom of tenon | Clearance between blade and shell | Speed | Temperature | Pressure |
|-------|--------------|------------------------------|-------------------------------|---------------------------------|-------|-------------|---------|
| -1    | 2.8          | 208.81                       | 7.21                          | 0.50                            | 30900 | 646.7       | 287.62  |
| 0     | 3.0          | 208.86                       | 7.31                          | 0.56                            | 31200 | 652.92      | 291.38  |
| 1     | 3.2          | 208.91                       | 7.41                          | 0.62                            | 31500 | 659.14      | 295.14  |

3.2 Mathematical model construction of turbine response surface
The box Behnken test design is selected, and the test scheme design and structural strength analysis are carried out through minitab18.0, a total of 62 groups. Based on the data obtained, the mathematical model of turbine response surface is constructed. Based on the design expert, the response surface is
constructed, and the value range of influencing factors, units and influencing factors are set. Among them, the influencing factors a is the blade root chamfer, B is the outer circle of turbine disk, C is the fillet of tenon groove bottom, D is the clearance between blade and shell, e is the speed, f is the temperature and G is the pressure, which corresponds to the influencing factors and data sheets of turbocharger turbine in Table 2. Taking the stress value of turbine blade as the response value, the mathematical model of stress response surface of turbine blade can be obtained as follows:

\[
Y = -137738587.5 + 340648A + 1310562B + 112919C - 32276D - 0.00495E + 0.0161F + 0.00174G - 0.0174B + 0.4779B^2 + 0.000065B^3 - 0.246618C + 1.30855C^2 - 0.333D + 12.077E + 0.1989F + 0.542G + 0.01705A - 0.779905A^2 - 0.03445A^3 + 0.346428E^2 - 0.1677F - 0.2005G^2
\]

(1)

Under any predicted value of the response surface of turbine blade, there is no obvious positive or negative correlation trend in the disordered distribution of the mechanical and biochemical residual of turbine blade, i.e. there is no other factor affecting the error distribution, as shown in Figure 8, which shows that the response surface of the stress value of turbine blade is well fitted.

**Figure 8.** Scatter distribution diagram of predicted residual stress of turbine blades

According to the predicted value and the actual value of the stress response surface model of turbine blade, the MAPE value calculated by the average error percentage is 0.6696%. The engineering experience shows that the error with the average error percentage less than 5% is acceptable, which shows that the stress response surface model of turbine blade is accurate and effective.

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\hat{y}_i - y_i}{y_i} \right| \times 100\% = 0.6696\%
\]

(2)

Similarly, the mathematical model of stress response surface of turbine disk is:

\[
Y = -1894132 - 46575.7A + 9380.818B + 17611.18C + 56092.03D + 6.588938E + 2519.234F - 132.276G + 219.2378A + 154.4695A^2 + 137.5871A^3 - 0.01705A^4 + 0.779905A^5 - 1.30855A^6 - 12.2162B - 0.03445B^2 + 0.346428E^2 - 0.1677F - 0.2005G^2
\]

(3)

Under any predicted value of the response surface of turbine disk, there is no obvious positive correlation or negative correlation trend, that is, there is no other factor affecting the error distribution. As shown in Figure 9, it is verified that the response surface of the stress value of turbine disk has a good fit.
According to the predicted value and the actual value of the stress response surface model of turbine blade, the MAPE value calculated by the average error percentage is 2.838%. The engineering experience shows that the error with the average error percentage less than 5% is acceptable, which shows that the stress response surface model of turbine blade has accuracy and validity.

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\bar{y}_i - y_i}{y_i} \right| \times 100\% = 2.838\%
\]  

(4)

3.3 Turbine reliability analysis

According to the mathematical model of stress response surface of turbine disk and turbine blade obtained in 2.2, Monte Carlo sampling is carried out. The range and distribution of influencing factors selected in this paper are shown in Table 3.

| Influence factor                  | Numbering | Parameter range   | Distribution method    |
|-----------------------------------|-----------|-------------------|------------------------|
| Leaf root chamfer/mm              | A         | 3.0±0.2           | Weibull distribution   |
| Turbine disk outer circle/mm     | B         | 208.86±0.05       | Lognormal distribution |
| Fillet at bottom of groove/mm     | C         | 7.31±0.1          | Weibull distribution   |
| Clearance between blade and shell/mm | D       | 0.56±0.06        | Normal distribution    |
| Speed/rpm                         | E         | 31200±300         | Normal distribution    |
| Temperature (℃)                   | F         | 652.92±6.22       | Normal distribution    |
| Pressure (MPa)                    | G         | 291.38±3.76       | Normal distribution    |

The probability density of parameters in lognormal distribution is:

\[
f(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma x}} \exp \left[ -\frac{1}{2\sigma^2} (\ln x - \mu)^2 \right], x > 0
\]  

(5)

The probability density of parameters in Weibull distribution is:

\[
f(x, \lambda, k) = \frac{k}{\lambda} \left( \frac{x}{\lambda} \right)^{k-1} e^{-\left( \frac{x}{\lambda} \right)^k}, x \geq 0
\]  

(6)

The yield strength of K491 at 600 ℃ is 822mpa as the response limit value, and the Pareto plot can be obtained by Monte Carlo sampling as shown in Figure 10 (a); the tensile limit strength of GH901 at 600 ℃ is 1010mpa as the response limit value, and the influence factor of turbine disk Pareto plot can be obtained by Monte Carlo sampling calculation as shown in Figure 10 (b).
The statistical table of Monte Carlo data can be obtained, as shown in Table 4. It can be seen that after Monte Carlo sampling in the table, the minimum stress value of turbocharger turbine blade is 722.94 MPa, the maximum value is 829.77 MPa, and the maximum value is greater than 822 MPa of yield strength of K491 material at 600 ℃, so it is necessary to optimize the reliability to reduce the stress value of turbine blade; the minimum stress value of turbocharger turbine disk is 971.42 MPa, the maximum value is 1024.7 MPa, and the maximum value is greater than 1010 MPa of GH901 material at 600 ℃, so it is necessary to optimize the reliability to reduce the stress value of turbine disk.

Through Monte Carlo sampling analysis, the reliability of turbine blade is 0.96 < 0.99, the reliability of turbine disk is 0.94333 < 0.99, which shows that the reliability of turbocharger turbine blade and turbine disk has optimization space.

### Table 4. Monte Carlo Statistics

|                | A/mm | B/mm | C/mm | D/mm | E/rpm | F/℃ | G/MPa | Y/MPa | P/MPa |
|----------------|------|------|------|------|-------|------|-------|-------|-------|
| mean           | 3.0132 | 208.86 | 7.3215 | 0.56  | 31200.0 | 652.92 | 291.38 | 807.58 | 999.99 |
| std.deviation  | 0.12705 | 0.023728 | 0.021084 | 0.02084 | 99.952  | 3.9962  | 1.999  | 1.4993  | 12.306  | 6.5759 |
| variance       | 0.016142 | 0.003137 | 4.4453e-4 | 9990.4  | 3.9962  | 2.2478  | 151.44 | 43.242  |
| skewness       | 0.00185 | 4.3586e-9 | 1.8207e-4 | 5.44e-7  | 1.36e-7  | 5.7464e-7 | 647.05 | 282780  |
| kurtosis       | 0.79413 | 0.13936 | 0.35955 | 0.12383 | 587.04  | 11.741 | 8.8056 | 109.29  | 53.254  |
| minimum        | 2.4737  | 208.79  | 7.0696  | 0.49808 | 30906.0 | 647.05  | 286.98 | 722.94  | 971.42  |
| maximum        | 3.2678  | 208.93  | 7.4291  | 0.62192 | 31494.0 | 658.79  | 295.78 | 829.77  | 1024.7  |
| range          | 0.79413 | 0.13936 | 0.35955 | 0.12383 | 587.04  | 11.741 | 8.8056 | 109.29  | 53.254  |

### 4 Turbine reliability optimizations

#### 4.1 Select design variables

According to figure 10, it can be seen that the main factors affecting the stress of turbine blade and turbine disk are summarized as shown in Table 5.

### Table 5. Main influencing factors of turbine blades and disks

| The main components | Reliability | Need to optimize or not | Influence factor                                      |
|---------------------|-------------|-------------------------|-------------------------------------------------------|
| Turbine disk        | 0.94333     | Yes                     | Leaf root chamfer                                     |
|                     |             |                         | Turbine disk outer circle                             |
|                     |             |                         | Rounded bottom of tongue and groove                   |
|                     |             |                         | Clearance between blade and shell                     |
| Turbine blade       | 0.96        | Yes                     | Rotating speed                                        |
|                     |             |                         | temperature pressure                                  |

In this paper, the design tolerance of the influencing factors in Table 5 and the three influencing factors of root chamfer, bottom fillet of tenon groove and clearance between blade and shell are
selected as design variables. In engineering, machining parameters are expressed as \( m^{\Delta/2} \), Where \( m \) is the target value of dimension parameter design, \( \Delta \) is the dimension tolerance, defined as the range of allowable dimension change, \( \Delta / 2 \) is the dimension tolerance, defined as the maximum allowable dimension change in one direction. In the actual machining process, design tolerance and dimension tolerance not only determine the reliability of the product, but also affect the processing cost of the product.

4.2 Set objective function

In this paper, the stress value of turbine blade, turbine disk and the machining cost of turbine blade and turbine disk are selected as the objective function. The common tolerance cost model is shown in Table 6, where \( a \) represents fixed cost, such as tool, installation, pre operation, etc., \( B \) represents the cost of producing a single part according to the specified size, \( \Delta \) represents tolerance, and all costs are calculated according to the parts [8].

| Model name                   | Model form                                      |
|------------------------------|-------------------------------------------------|
| Linear model                 | \( CP(\Delta) = A - B \Delta \)                |
| Exponential model            | \( CP(\Delta) = Be^{-m\Delta} \)               |
| Reciprocal square model      | \( CP(\Delta) = A + B/\Delta^2 \)              |
| Power index model            | \( CP(\Delta) = Bexp(-m\Delta^k) \)            |
| Reciprocal Power Index Model | \( CP(\Delta) = Be^{-m\Delta/\Delta^k} \)      |

In order to adapt to the variety of parts geometry, researchers based on the above model form, according to the actual situation of our country, considering the four machining features of the outer circle feature, hole feature, positioning feature and plane feature, put forward the cost function based on the cost data of domestic products. These four tolerance processing cost functions are shown in Table 7, and the unit of tolerance \( \Delta \) is mm [8].

| Model name       | Model form                                      |
|------------------|-------------------------------------------------|
| Outside feature  | \( C(\Delta) = \frac{15.1138e^{-0.2841\Delta} + \Delta}{1.151063 + 0.01508} \) \( \Delta \leq 0.11 \) |
| Inner hole features | \( C(\Delta) = \frac{13.3114e^{0.001504\Delta} + 7.6593e^{-0.1771\Delta}}{1.463467} \) \( \Delta > 0.11 \) |
| Positioning feature | \( C(\Delta) = \frac{13.4998e^{0.000848\Delta} + 13.073e^{-0.546\Delta}}{2.28205} \) \( \Delta \leq 0.11 \) |
| Plane feature     | \( C(\Delta) = \frac{5.026e^{-0.8001\Delta} + \Delta}{1.273338 + 0.3927\Delta + 0.1176} \) \( \Delta \leq 0.165 \) |

In formula 7, and the machining cost model of turbine disk is shown in formula 8, where \( \Delta_1 \) is the common clearance between turbine blade and shell The difference range, \( \Delta_2 \) is the tolerance range of the fillet at the bottom of the tenon, and \( \Delta_3 \) is the tolerance range of the blade root chamfer. The value range is shown in Table 8.
\[
\cos Y = 15.1138 \exp(-42.2874 \Delta_y) + \Delta_y / (0.861 + 0.01508)
\]
(7)
\[
+13.3114 \Delta_z \exp(-0.0438 / \Delta_z) + 7.6593 \exp(-25.1731 \Delta_z)
\]
\[
+13.3114 \delta \exp(-0.0438 / \delta) + 7.6593 \exp(-25.1731 \delta)
\]

\[
\cos P = 15.1138 \exp(-42.2874 \Delta_p) + \Delta_p / (0.8611 + 0.01508)
\]
(8)
\[
+13.3114 \Delta_r \exp(-0.0438 / \Delta_r) + 7.6593 \exp(-25.1731 \Delta_r)
\]

4.3 Set constraints
The constraints are the upper and lower limits of the influencing factors in the design variables and the upper and lower limits of the tolerance. The upper and lower limits of the influencing factors are shown in Table 4. Based on the machining capacity, jiangzengwei provides the upper and lower limits of the tolerance of the three main influencing factors, i.e. the root chamfer, the fillet at the bottom of the tenon groove, and the clearance between the blade and the shell, as shown in Table 8.

Table 8. Main influencing factors

| Size name                                      | Distribution form     | Parameter target | Tolerance lower bound | Tolerance upper bound |
|-----------------------------------------------|-----------------------|------------------|-----------------------|-----------------------|
| Leaf root chamfer/mm                          | Weibull distribution  | 3.000            | 0.200                 | 0.400                 |
| Turbine blade and shell clearance (wire)      | Normal distribution   | 56.0             | 4.0                   | 12.0                  |
| Fillet of bottom of tongue and groove/mm      | Weibull distribution  | 7.310            | 0.022                 | 0.200                 |

4.4 Reliability optimization result analysis
NSGA-II algorithm is an improved multi-objective genetic algorithm based on fast non inferior sorting. Its efficiency lies in using a non dominated classification program to simplify the multi-objective to a fitness function. The algorithm can solve any number of objective problems and has a wide range of applications in engineering. Its deterministic optimization model is:

Minimize \( f_m(x), m = 1, 2, \ldots, M; \)

Subject to \( g_j(x) \leq 0, j = 1, 2, \ldots, J; \)

\( X^L_i \leq X_i \leq X^U_i, i = 1, 2, \ldots, I; \)

(9)

Where, \( x \) is the ith design variable; \( I \) is the total number of design variables; \( X^L_i \) and \( X^U_i \) is the lower and upper limit of the value of the ith design variable; \( f_m(x) \) is the m-th sub objective function; \( m \) is the total number of sub objective functions; \( g_j(x) \) is the j-th inequality constraint condition; \( J \) is the total number of inequality constraints [9].

Based on iSIGHT, NSGA-II algorithm is used to optimize 6Sigma reliability, and the summary of optimization data is shown in Table 9, as shown in Figure 11 (a), (b) is the probability distribution diagram of turbine disk stress and turbine blade stress optimization, in which the maximum value of turbine disk stress is 1006.3mpa < 1010mpa, meeting the material strength requirements; the maximum value of turbine blade stress is 815.58mpa < 822mpa, meeting the material strength requirements.
Table 9. Optimized data summary table

| Optimization parameters | Initial value | Optimized value | Optimization ratio/% |
|-------------------------|---------------|----------------|---------------------|
| △A/mm                  | 0.4           | 0.29447        | 26.3825             |
| △C/mm                  | 0.2           | 0.19892        | 0.54                |
| △D/mm                  | 0.12          | 0.10221        | 14.825              |
| Y/MPa                  | 829.77        | 789.99         | 4.7941              |
| P/MPa                  | 1024.7        | 993.82         | 3.0316              |
| Cost Y                 | 8.069         | 6.8176         | 15.5087             |
| Cost P                 | 3.433         | 3.296          | 3.9907              |

Figure 11(a). Probability distribution of turbine disk

Figure 11(b). Probability distribution of turbine blades

As shown in Figure 12 (a) - (d), the six sigma level chart of turbine disk, turbine blade, turbine disk processing cost and turbine blade processing cost shows that they all have high sigma level, and the reliability of turbine disk and turbine blade is 1 > 0.99, which meets the reliability requirements of relevant specifications and has high reliability.

Figure 12(a). Turbine disc 6Sigma level

Figure 12(b). Turbine blade 6Sigma level

Figure 12(c). 6 sigma level chart of turbine disk processing cost

Figure 12(d). Turbine blade machining cost 6Sigma level chart
4.5 Verification of reliability optimization results

According to the parameters of Six Sigma reliability optimization based on iSIGHT using NSGA-II algorithm, the structural strength analysis of marine low-speed diesel supercharger under complex load is carried out. The optimized parameters of the main influencing factors are root chamfer 2.9322mm, outer circle 208.82mm, bottom fillet 7.3791mm, clearance 0.52317mm, rotating speed 31159rpm, temperature 648.84 ℃ and pressure 290.95mpa. The stress nephogram of the turbine disk is shown in Figure 13 (a). The maximum stress of the turbine disk is 967.25mpa, which is 2.6735% different from the optimized value. The stress nephogram of the turbine blade is shown in Figure 13 (a) As shown in FIG. 13 (b), it can be seen that the maximum stress of turbine blade is 755.88mpa, which is 4.3178% different from the optimized value, and the difference between the two values is less than 5%. Therefore, the data obtained by using NSGA-II algorithm to optimize 6Sigma reliability based on iSIGHT is of high practical reference value.

Figure 13(a). Stress distribution of turbine disk

Figure 13(b). Stress distribution of turbine blade

5 Conclusion

In this paper, the reliability analysis and optimization of jth series marine low-speed diesel supercharger turbine of Chongqing JIANGZENG Shipbuilding Heavy Industry Co., Ltd. is carried out. The response surface mathematical model and Monte Carlo sampling method are used to obtain the turbine disk reliability of 0.943 and turbine blade reliability of 0.96. Based on NSGA-II multi-objective genetic algorithm, the stress value and processing cost of turbine disk and turbine blade are taken for the purpose of reliability optimization, the reliability of turbine disk and turbine blade is 1, the stress value of turbine blade is 4.7941%, the stress value of turbine disk is 3.0136%, the machining cost of turbine blade is 15.5087%, and the machining cost of turbine disk is 3.9907%. Finally, the results of genetic algorithm and simulation analysis are compared, the difference is less than 5%, which shows that the data based on NSGA-II multi-objective genetic algorithm has practical reference value.

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