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船用柴油机增压器辅助止推面可靠性设计优化

Optimization of Reliability Design of Auxiliary Push Surface for a Marine Diesel Engine Supercharger

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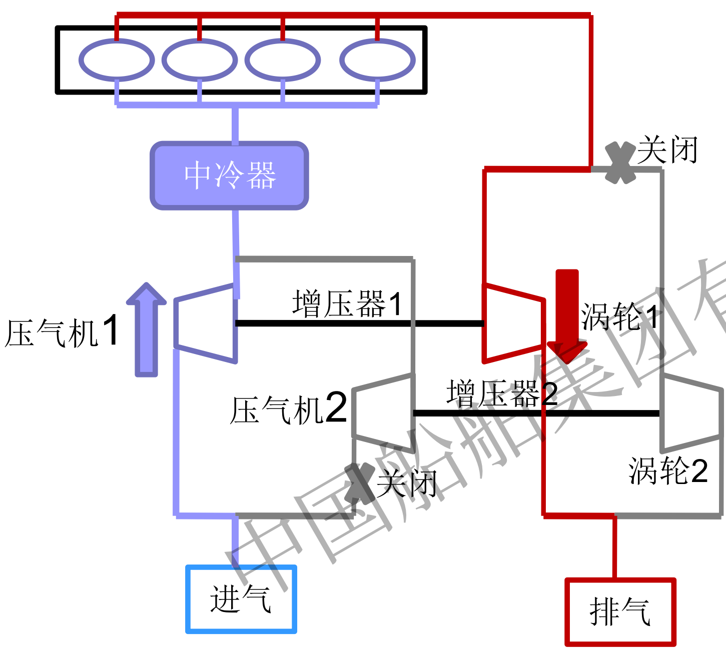
主要内容（ Content ）

一、研究背景及问题
Research Background and Problems

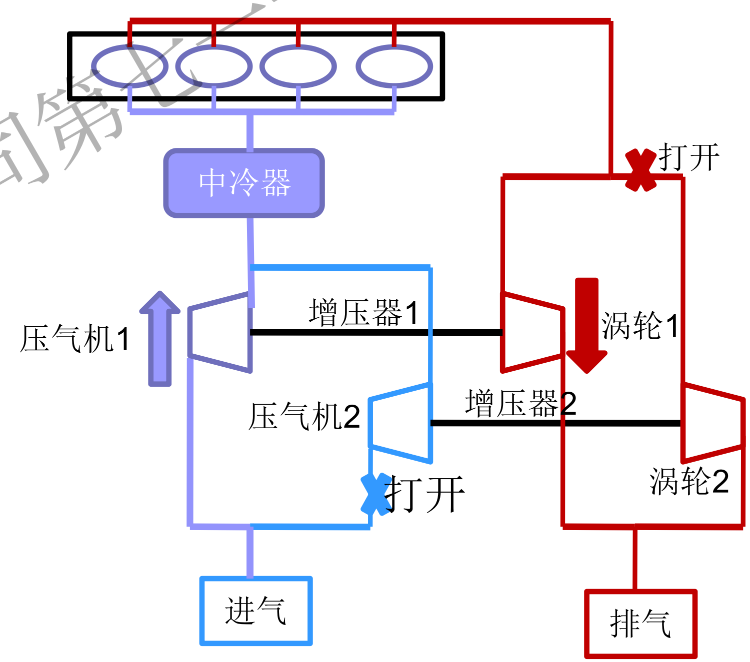
- 柴油机是国民经济中应用广泛的主要动力机械之一，其可靠性是重要质量指标，不仅是科研者、生产者所应考虑的，也是使用者最为关切的。可靠性对柴油机运行的经济性和安全性具有头等重要意义。
- Diesel engine is one of the most widely used power machines in national economy. Reliability is of primary importance to the economy and safety of diesel engine operation.
- 随着船舶柴油机强化指标的不断提高，相继增压、两级相继增压等高增压技术应用程度越来越高，这就使得增压器各项性能指标及可靠性必须进一步提高。
- With the continuous important of ship diesel engine strengthening index, successive pressurization and two-stage pressurization are the necessary technical means, which requires the performance index and reliability of supercharger to be further improved.

一、研究背景及问题
Research Background and Problems

❑ 相继增压原理
Sequential Supercharging Principle



（a）低速，增压器1开，增压器2关

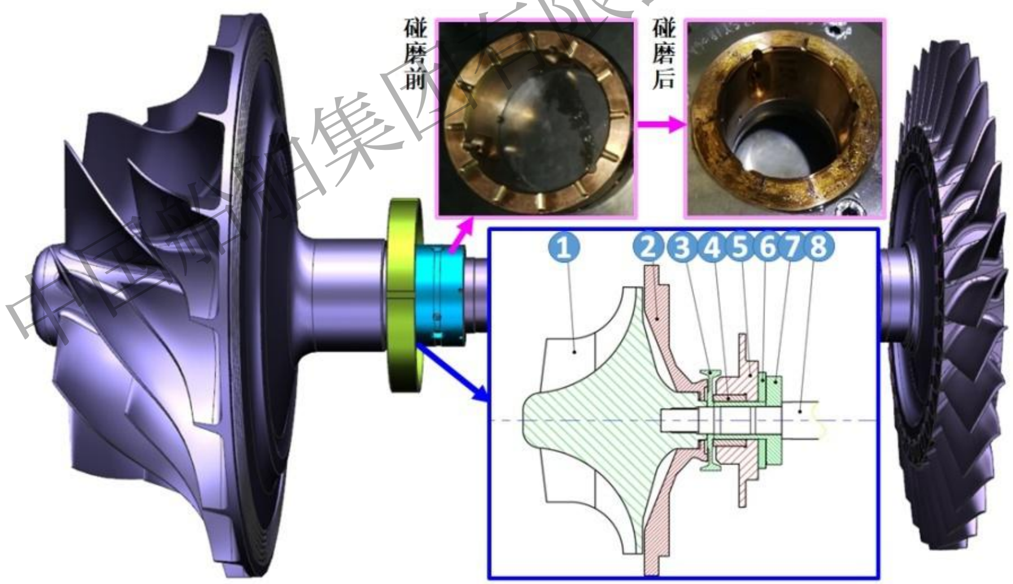


（b）高速，增压器1和2同时开

一、研究背景及问题

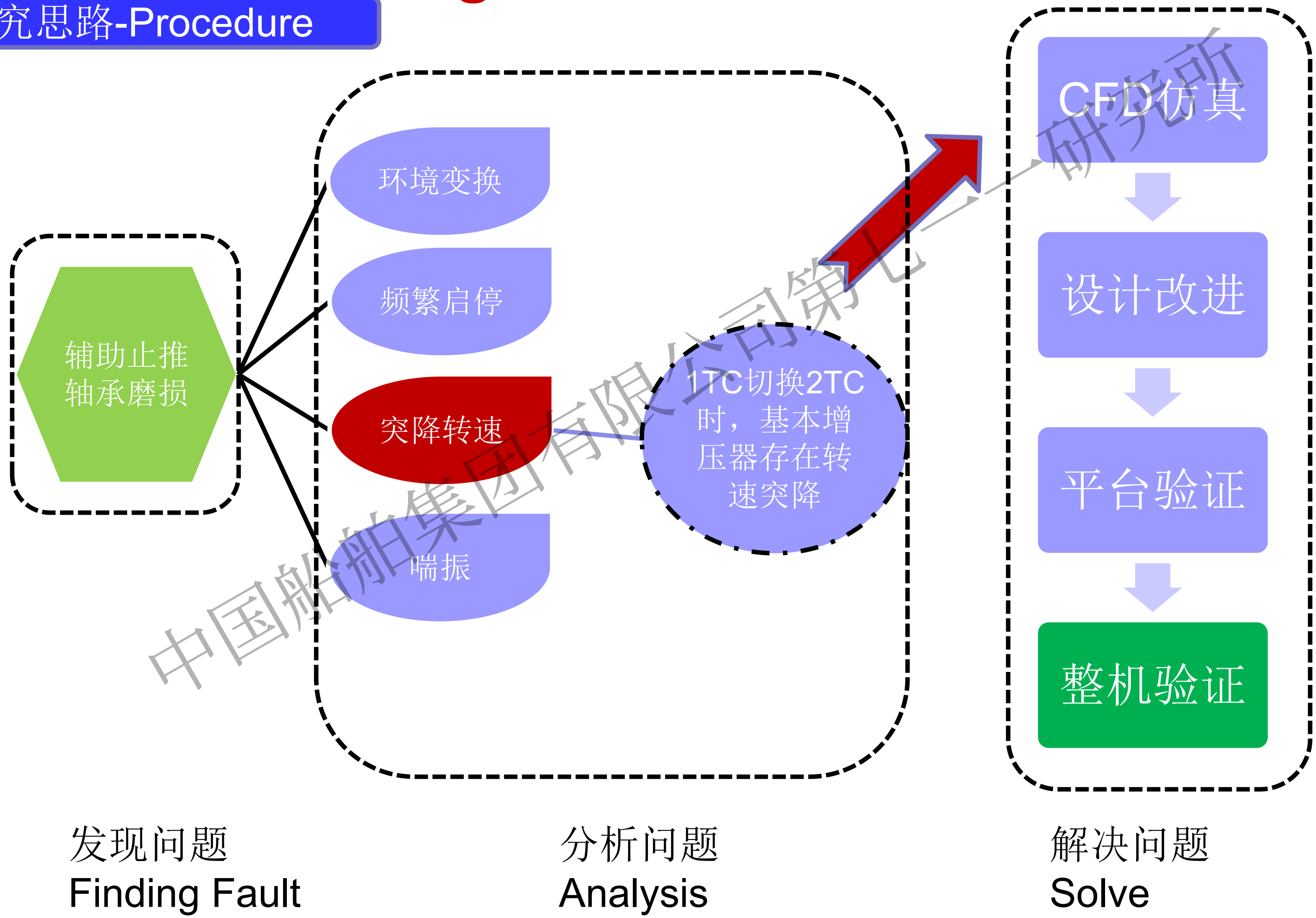
Research Background and Problems

- 船用柴油机高指标轴流基本增压器在性能试验过程中发生辅助止推面的碰磨故障，开展辅助止推总成设计优化，提高关键零部件可靠性。
- The design optimization of optimization of auxiliary thrust assembly is carried out in the process of perfomance test of a certain marine diesel engine with high index axial flow supercharger, improve the reliability of key components.



一、研究背景及问题
Research Background and Problems

研究思路-Procedure



二、CFD仿真建模
CFD Simulation Model

故障描述-Fault Description

●输入边界-匹配柴油机性能参数

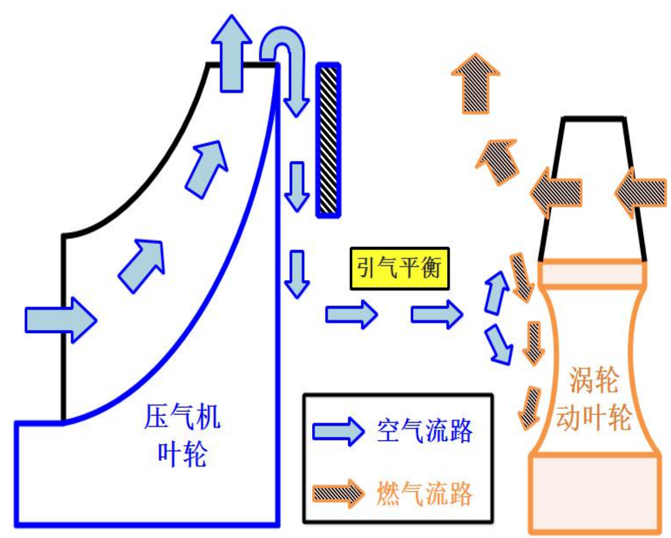
在匹配相继增压的柴油机性能试验过程中，如表1所示，工况点1至工况点2是增压模式由1TC切换至2TC的时间点，之后增压器转速迅速下降，至工况点5之后又逐渐向稳定运行转速恢复。

●Input Boundary-Matching Diesel Engine Performance Parameters

As shown in table 1, from the operating 1 to the operating 2, the turbocharging mode changes from 1 to 5 and then gradually recovers to the stable operating speed.

表1 柴油机1TC切换至2TC时增压器试验采集数据
Table 1

工况点	采集时间	压气机出口相对压力	涡轮进口相对压力	增压器相对转速
1	10:12:40	0.9861	1.0000	1.0000
2	10:12:41	0.6619	0.3876	0.8625
3	10:12:42	0.3088	0.2023	0.7286
4	10:12:44	0.2229	0.1467	0.5799
5	10:12:46	0.4630	0.3523	0.6914



二、CFD仿真建模
CFD Simulation Model

故障描述- Fault Description

●相继增压用的增压器转子系统辅助止推面的碰磨故障发生在工况点1至工况点5的时间段内。在此过程中，压气机端和涡轮端的总体压力水平也呈现出先迅速下降而后又上升的变化规律。

●The grinding failure of the auxiliary thrust surface of the turbocharger rotor system occurs in the period from working point1 to 5 .In this process, the total pressure levels at compressor and turbine ends also show a rapid decrease and then rise.

表1柴油机1TC切换至2TC时增压器试验采集数据
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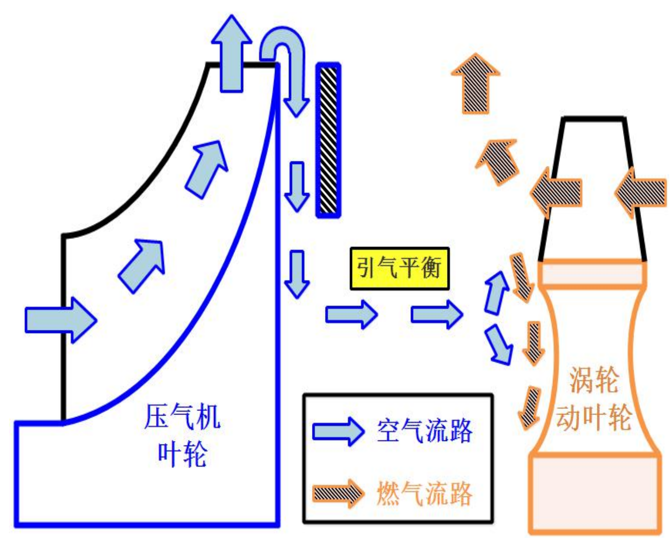


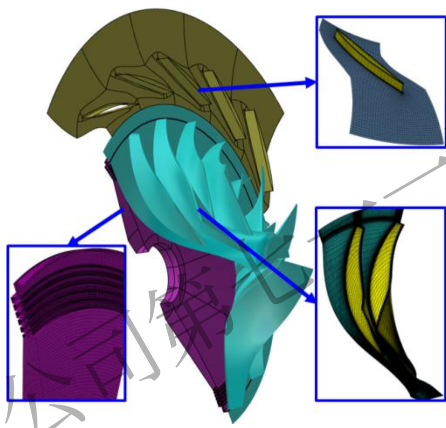
二、CFD仿真建模
CFD Simulation Model

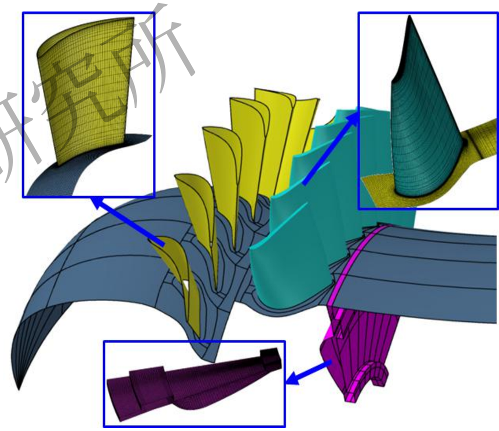
- 采用用轴流增压器转子系统轴向受力理论分析与数值仿真结合的方法，对增压模式切换时间段内转子系统轴向力的变化规律进行深入研究。

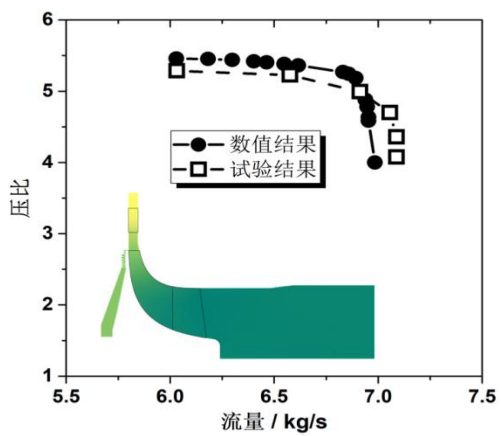
  Based on the analysis of axial force and numerical simulation of axial turbocharger rotor system , the axial variation of rotor system during the switching period of turbocharger mode is studied.

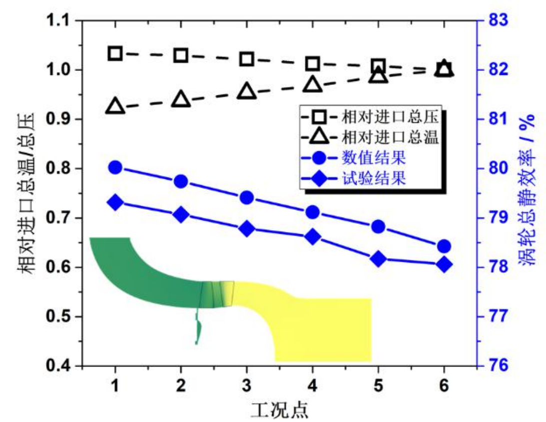
- 对压气机和涡轮的数值计算结果和试验结果分别进行了对比，其中的试验数据是增压器试验台上获取的，从图看出，数值和试验所获得的压气机性能曲线基本吻合。

  It can be seen from the diagram that the numerical value is basically consistent with the performance curve of the compressor obtained by the test .



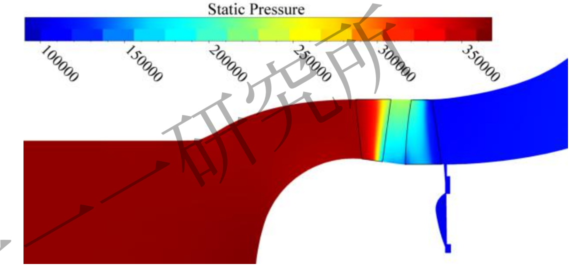


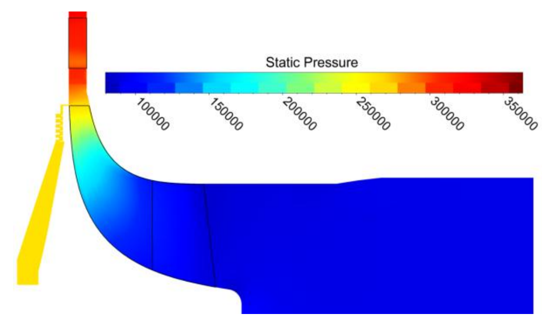


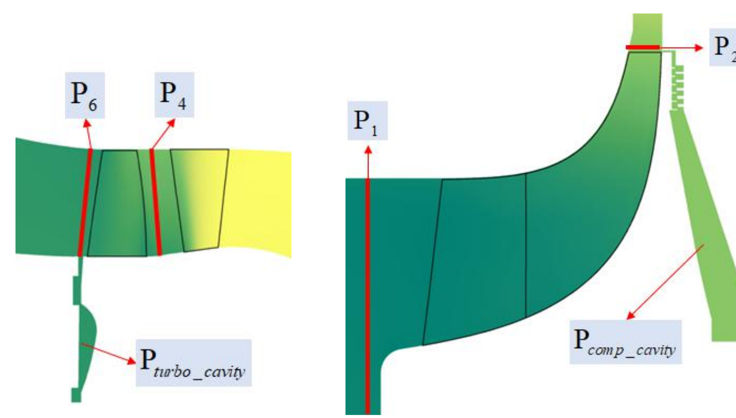


三、仿真结果及规律分析
Simulation Results and Law Analysis

- **压气机与涡轮数值计算结果**
  Numerical results of compressor and turbine
- 对于压气机叶轮后的盘腔和涡轮轮盘后的盘腔，其内部整体压力水平与压气机叶轮出口或涡轮动叶出口压力随工况变化规律一致。
  For the disc cavity behind the compressor impeller and the turbine wheel disc, the variation of the pressure at the outlet of the compressor impeller or the outlet of the turbine moving blade with the operating conditions.
- P1、P2 和 P4、P6 为通过数值计算直接获得的典型位置处的质量流量加权平均后的静压值，静压值加权平均位置如图所示。
  P1\p2 and p4\p6 are the static pressure values , the weighted average position of the static pressure value is shown in fig.





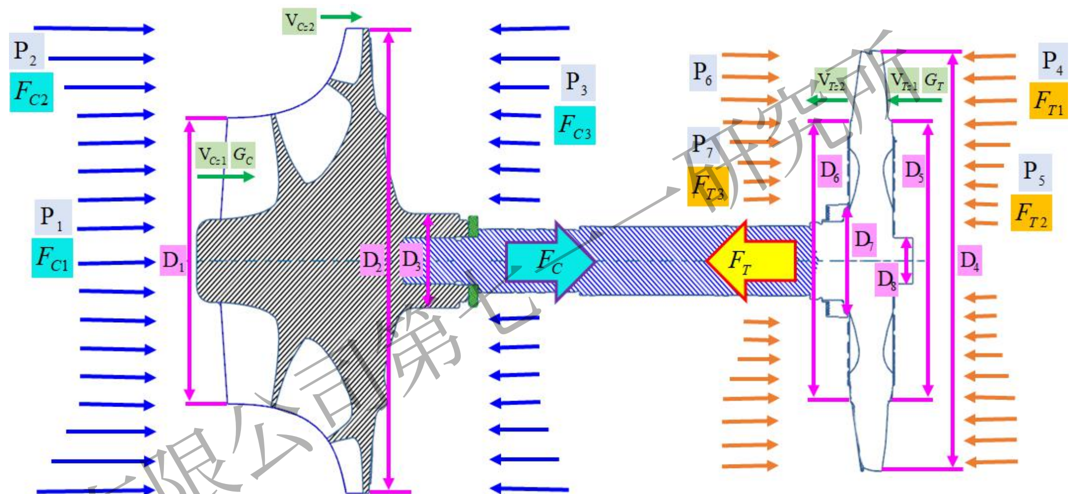


三、仿真结果及规律分析

Simulation Results and Law Analysis

●结合该类型轴流增压器结构特点，绘制了图8所示的增压器转子受力情况。
Combined with the structural characteristics of this type of axial flow supercharger, the stress of the rotor of the supercharger shown in fig.8 is drawn

●转子系统各轴向分力的计算公式由式（1）至式（8）给出:
From formula 1 to 8 ,the formula for calculating each axial force of rotor system given:



$$F_{C1}=\frac{\pi D_1^2}{4}P_1+G_C(V_{Cz1}-V_{Cz2}) \quad (1)$$

$$F_{C2}=\int_{r_1}^{r_2}P_2\left(\frac{r}{r_2}\right)^2\cdot 2\pi r dr=\frac{\pi}{8}P_2\left[D_2^2-D_1^2\left(\frac{D_1}{D_2}\right)^2\right] \quad (2)$$

$$F_{C3}=P_3\cdot\frac{\pi}{4}\left(D_3^2-D_2^2\right) \quad (3)$$

$$F_C=F_{C1}+F_{C2}-F_{C3} \quad (4)$$

$$F_{T1}=\frac{\pi\left(D_4^2-D_5^2\right)}{4}(P_4-P_6)+G_T(V_{Tz1}-V_{Tz2}) \quad (5)$$

$$F_{T2}=\int_{r_8}^{r_5}P_4\left(\frac{r}{r_5}\right)^2\cdot 2\pi r dr=\frac{\pi}{8}P_4\left[D_5^2-D_8^2\left(\frac{D_8}{D_5}\right)^2\right] \quad (6)$$

$$F_{T3}=P_7\cdot\frac{\pi}{4}\left(D_6^2-D_7^2\right) \quad (7)$$

$$F_T=F_{T1}+F_{T2}-F_{T3} \quad (8)$$

三、仿真结果及规律分析

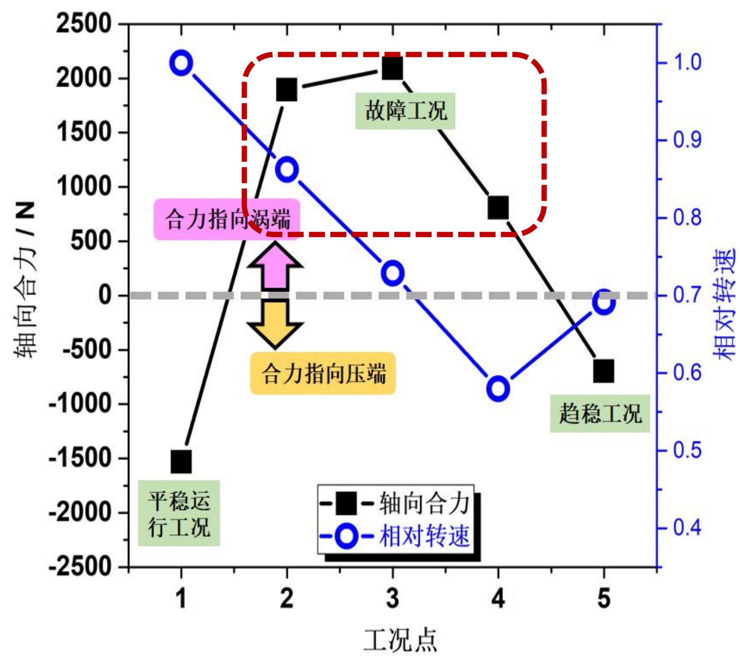
Simulation Results and Law Analysis

●表2给出了压端/涡端各截面压力仿真计算结果，可以看出在进行1TC到2TC切换之后的工况2至工况4时间段内，涡轮端整体压力水平都是明显小于压气机端的。
增压模式的切换使得转速突然下降，涡轮端压降速率也高于压气机端，这使得增压系统轴向受力方向出现反转，轴向合力在工况2至工况4的3秒内，方向始终指向涡端，使得在该时间段内材质较软的辅助止推面受力，最终导致如图1所示的碰磨情况。

●The results show that after switching the supercharger mode from 1TC to 2TC, the axial force always points to the vortex end in 3 seconds from working condition 2 to 4 ,and the material of the auxiliary thrust surface is soft , which leads to the failure of the final guide.

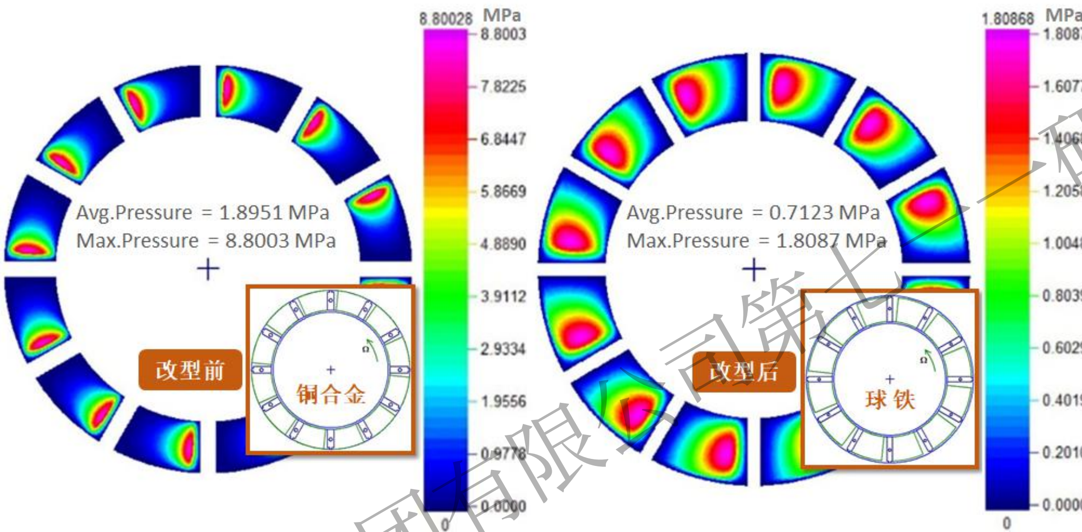
表2压端/涡端各截面压力仿真计算结果
Table 2

压力/kPa	工况1	工况2	工况3	工况4	工况5
P1	92.20	95.84	97.64	98.93	98.96
P2	295.30	236.29	185.02	148.90	174.62
Pcomp_cavity	262.05	214.72	159.08	147.96	151.67
P4	195.58	113.31	92.37	93.95	137.16
P6	109.44	86.45	78.44	84.41	126.24
Pturbo_cavity	89.58	69.97	78.20	83.19	124.72



四、设计改进及可靠性提升验证

Design Improvement and Reliability Verification



- 通过对前述故障情况的分析，对原辅助推力轴承进行了改型设计。加大了辅助推力轴承的承载面积，同时将其材料由原来的铜合金替换为耐磨性更好的球铁材料。
- 原辅助推力轴承和改型后辅助推力轴承计算模型及其承载力计算结果如图所示:改型后的辅助推力轴承平均承载能力是原来的2.7倍，结果满足设计改进要求。
- Increasing bearing area and material hardness can meet the design requirement.

四、设计改进及可靠性提升验证

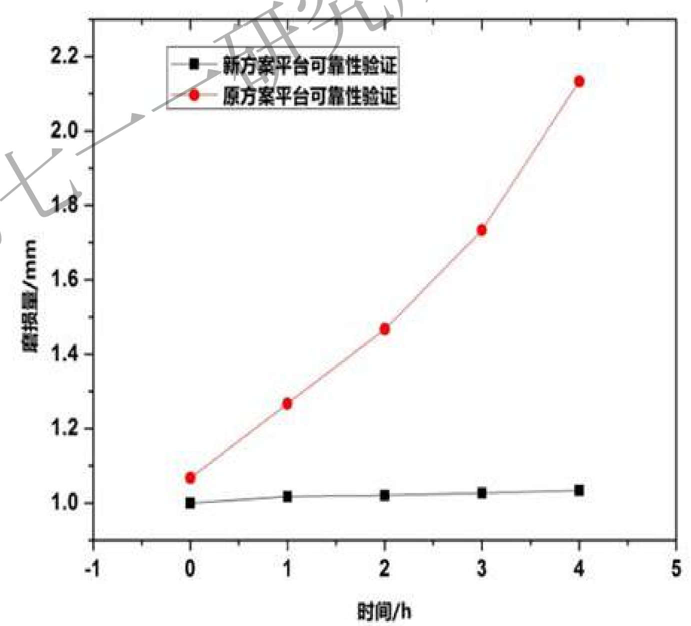
Design Improvement and Reliability Verification

- **增压器平台验证**

通过在增压器平台试验上开展低速喘振试验，模拟1TC切换2TC时的轴向力由压端指向涡端的情况，如图所示，在同样的考核时间内，改进后方案的磨损量变化很小，极大提高了增压器整体可靠性。

- **Supercharger Platform Verification**

Through the low speed surge test carried out on the turbocharger platform test, as show in the figure, the wear amount of the improved scheme changes very little during the same examination time, which greatly improves the overall reliability of the supercharger.



四、设计改进及可靠性提升验证

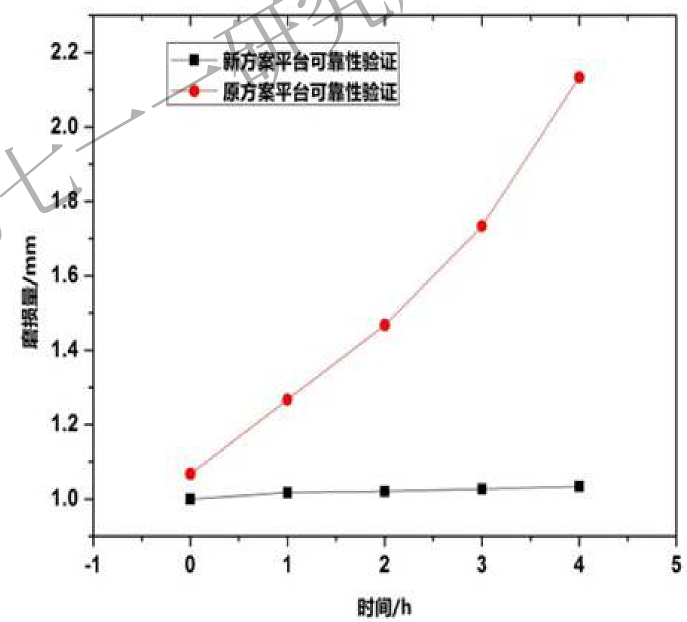
Design Improvement and Reliability Verification

- **增压器配机可靠性验证**

  装配有改进后的辅助止推轴承总成方案的增压器随柴油机进行可靠性考核试验，整个试验过程中多次进行增压器例行拆检维护检查，基本、受控增压器轴向游动量均在规定范围内，增压器本体无故障发生，整机可靠性明显改善。

- **Matching Machine Reliability Verification**

  The improved auxiliary thrust bearing assembly scheme carries on the reliability examination test with the diesel engine, the supercharger body has no fault, and the reliability of the whole machine is obviously improved.



五、结论

Conclusion

- 通过对相继增压船用柴油机性能试验过程中，增压模式切换时增压器辅助止推面发生碰磨故障的情况进行理论分析和数值仿真，得出以下几点结论：

  through the therоretical analysis and numerical simulation of the failure of the auxiliary thrust surface of the supercharger during the performance test of marine diesel engine with successive supercharger, the following conclusions are drawn:

（1）增压器辅助止推面的碰磨故障是由于增压模式切换时，转子轴向合力方向出现短时反向导致的。

The grinding failure of the auxiliary thrust surface of supercharger is due to the short time reverse of the axial force direction of the rotor when the booster mode is switched.

五、结论

Conclusion

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（2）在故障发生时数据采集工况点所处的时间段内，增压器轴向合力先反向而后又回复到正常状态，整个辅助止推面受碰磨时间大概持续3秒。

The axial force of the supercharger is reversed and then returned to the normal state during the time period of the data acquisition working condition when the fault occurs, and the whole auxiliary thrust surface is subjected to rubing for about 3 seconds.

五、结论

Conclusion

- （3）对于采用相继增压模式的柴油机增压器，考虑到模式切换时增压器轴向受力的变化特点，转子系统上的辅助止推面应选用硬度更大的材质，并根据本文所计算出的故障工况下辅助止推面所受最大轴向力的水平，适当增大辅助止推轴承的承载面，以确保后续增压器和柴油机的可靠稳定运行。

  for the diesel turbocharger with successive supercharging modes, considering the changing characteristics of axial force of the supercharger during mode switching, the auxiliary thrust surface on the rotor system should be made of material with greater hardness , and the bearing surface of the auxiliary thrust bearing should be increased appropriately according to the level of the maximum axial force of the auxiliary thrust surface under the fault condition calculated in this paper to ensure the reliable and stable operation of the subsequent supercharger and diesel engine.

五、结论
Conclusion

- 本文改进措施使得辅助推力轴承平均承载能力提升为原来的2.7倍。试验结果表明，改型后的推力轴承在故障工况下推力面和油楔的磨损状态较原型明显改善,增压器及整机的可靠性得到极大改进。
- The test results show that the wear state of the modified thrust bearing is obviously better than the prototype, and the reliability of the supercharger and the whole machine is great improved.

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谢谢！