气缸套抗穴蚀设计及试验验证
Liner cavitation resistant and verification

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研究背景
BACKGROUND

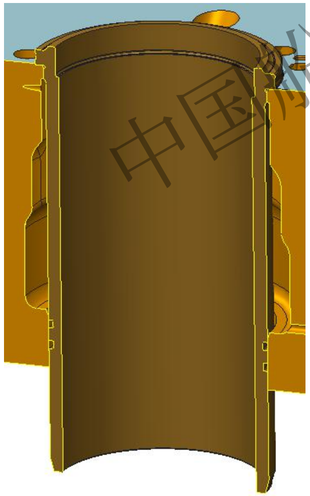
研究背景 BACKGROUND

- **穴蚀是湿式气缸套常见故障模式，直接影响柴油机使用寿命及可靠性**

  Cavitation is the common failure mode of wet liner, and influenced the reliability and life of engine

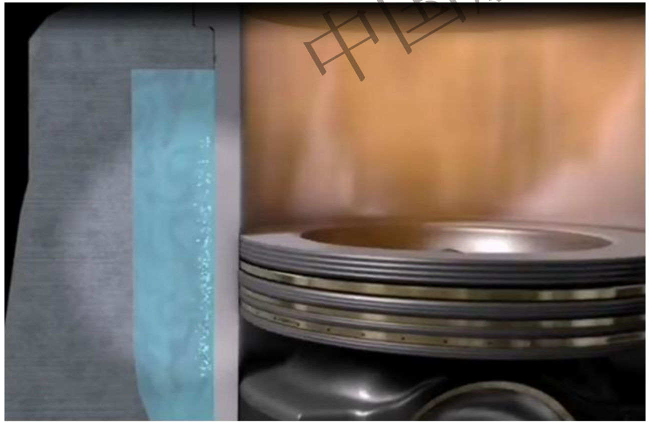
- **缸套外表面出现局部聚集穴群，进一步出现外壁穿孔、裂纹，导致冷却液渗进气缸，并流入到油底壳，严重时导致拉缸、曲轴烧瓦等故障**

  Cavitation cause crack and holes, lead coolant penetrate into the crankcase , and lead liner or main bearing scuffing severely



研究背景BACKGROUND

- 缸套高频振动使冷却液局部压力下降到空化临界值时，溶于冷却液中的气体便以气泡的形式分离出来，当压力超过一定值时便发生溃灭
  Coolant cannot keep up with the liner vibrations, and pressure drops below the vapor pressure, bubbles form. pressure rises above the vapor pressure again, then the bubbles implode suddenly
- 气泡重新液化或溶于冷却液中，冷却液向气泡中心高速运动而产生水击现象，产生极大的冲击力和高温
  Bubbles collapsing causes high pressure impulses and temperatures
- 气缸套外表面在这种力的反复作用下，缸套水腔表面材料因疲劳而产生脱落，出现穴蚀
  Repeated occurrence of the cavitation process leads to erosion of the liner.



研究背景BACKGROUND

1 **活塞敲击力**
Piston slap force
振动激励源
Vibration excitation

2 **气缸套刚度**
Liner stiffness
振动速度响应
Vibration velocity

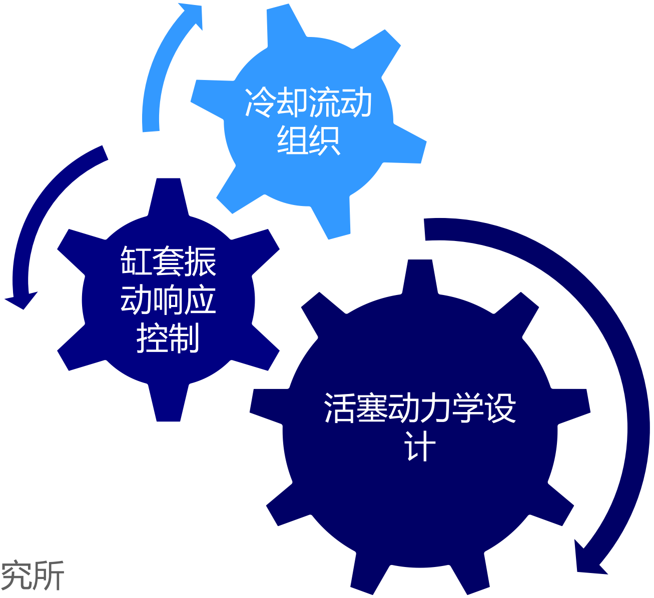
3 **气缸套表面材料**
Liner material
抗穴蚀能力
Cavitation resistance

4 **冷却流动组织**
Fluid dynamics
气泡生成倾向
Bubble tendency

5 **冷却液性能**
Fluid property
气泡生成倾向
Bubble tendency

研究背景BACKGROUND

- **如何提升抗穴蚀能力？**
  how to improve the design to increase the cavitation resistance
  - 活塞动力学设计及优化，降低活塞敲击力
    Optimize piston dynamics to decrease the piston slap force
  - 气缸套设计及优化，降低气缸套振动速度响应
    Optimize liner to decrease the vibration velocity
  - 冷却流动组织优化，降低冷却液空化倾向
    Optimized fluid dynamics to decrease the cavitation tendency



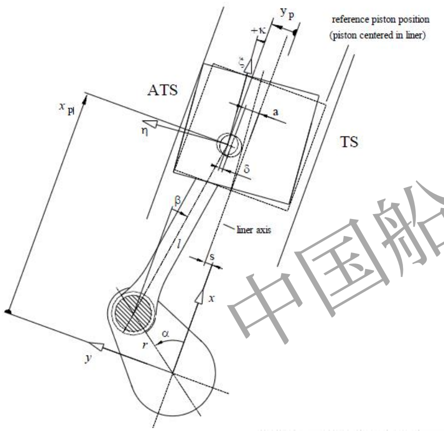
02

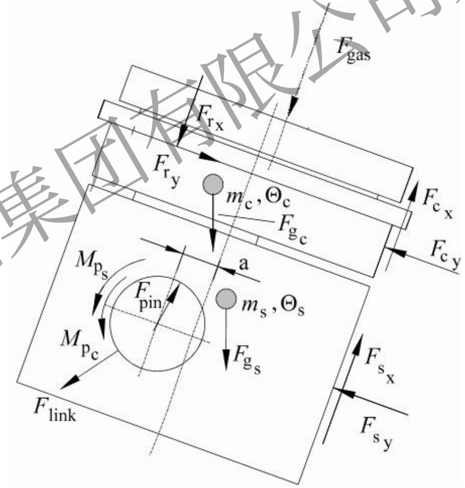
活塞动力学设计

PISTON DYNAMICS

活塞动力学设计PISTON DYNAMICS

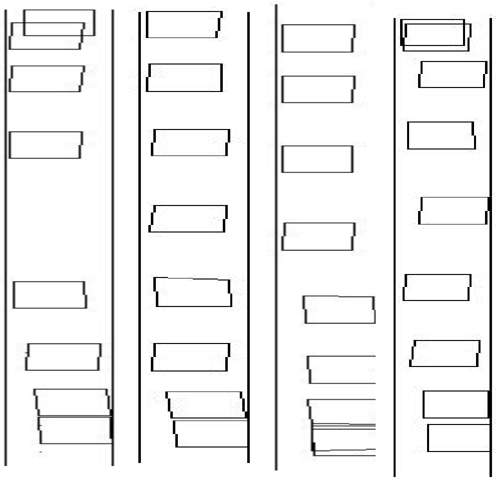
- **活塞在燃烧气体压力和往复惯性力的作用下，周期性地作横向运动和绕活塞销轴的转动，对缸套产生敲击和刮擦，使得缸套发生振动**
- **Piston move in axial and rotate with pin under the combustion and inertial force, piston slap force excite the liner and cause liner vibration**





$$[M]\{\ddot{s}\} = \{F\}$$

$$[I]\{\ddot{\phi}\} = \{T\}$$

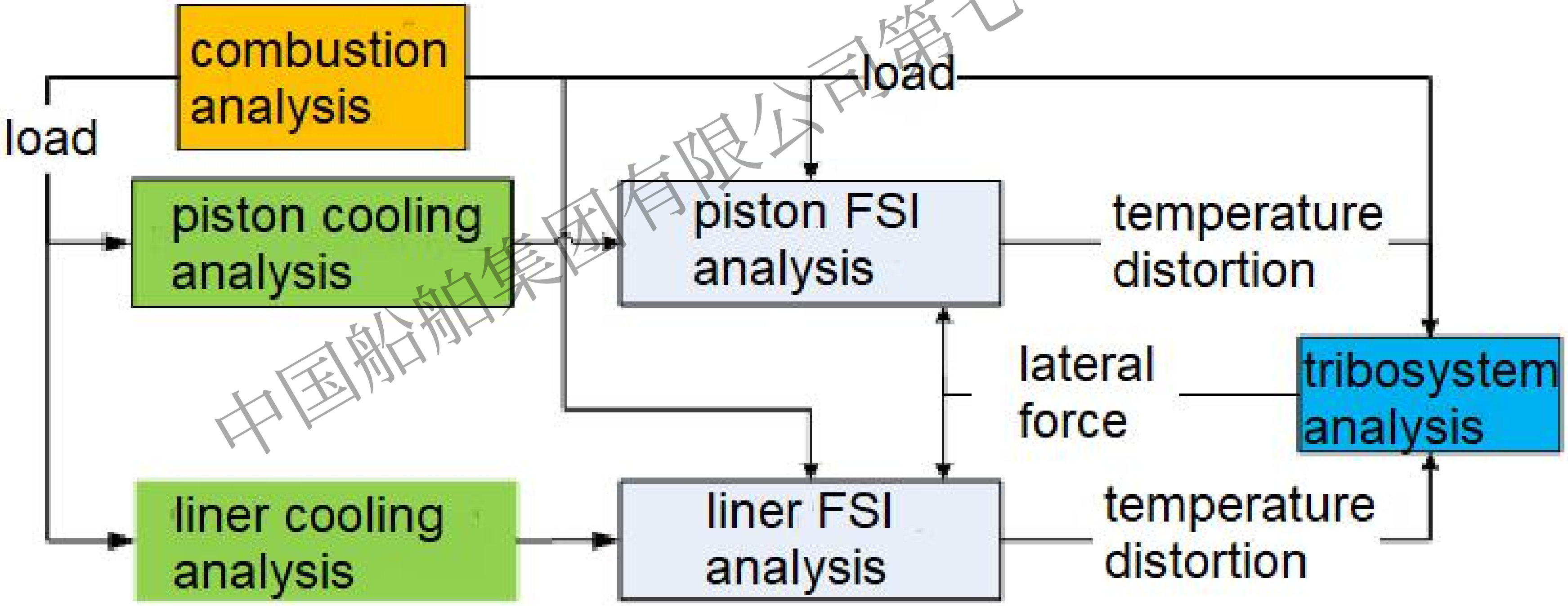


活塞运动轨迹
Piston motion track

活塞动力学设计PISTON DYNAMICS

- **综合缸套、活塞的温度和结构变形，为动力学设计分析提供精准边界**

  Consider Liner and piston temperature and distortion into piston dynamic design



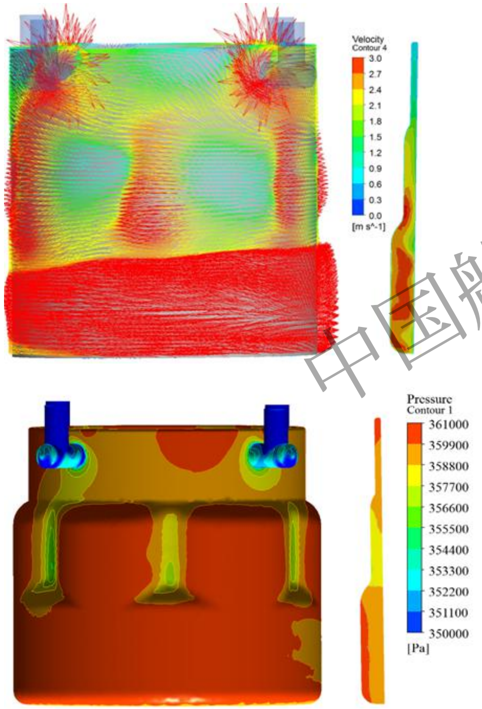
活塞动力学设计PISTON DYNAMICS

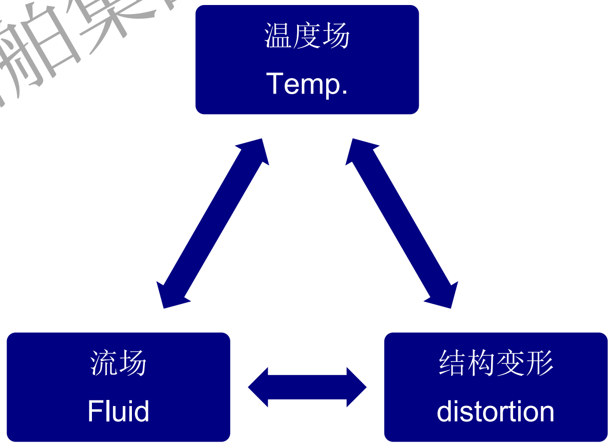
- □ **通过缸套水腔流动CFD仿真，确定缸套水腔冷却液流动特性**

  Obtain coolant flow property through water jacket CFD simulation

- □ **根据热-机耦合分析，获得气缸套变形和温度发布**

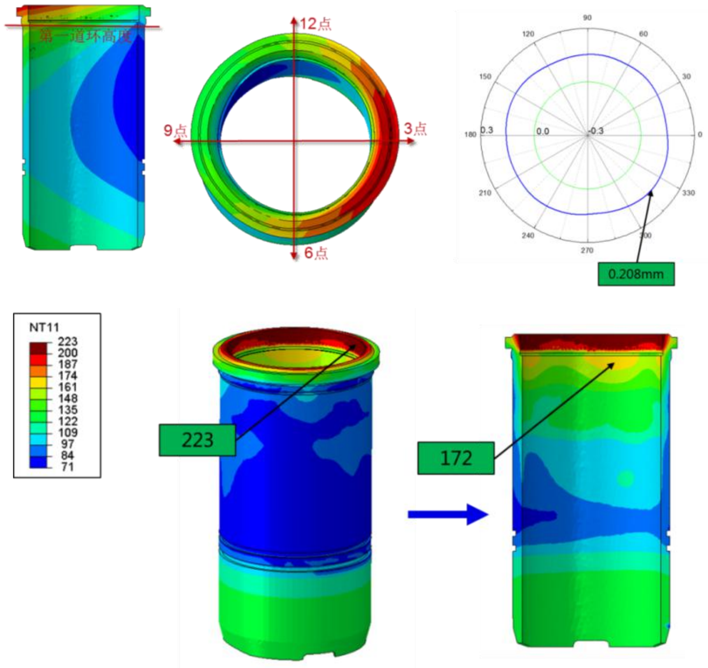
  Obtain liner temperature and distortion through thermal-structure analysis




温度场
Temp.

流场
Fluid

结构变形
distortion



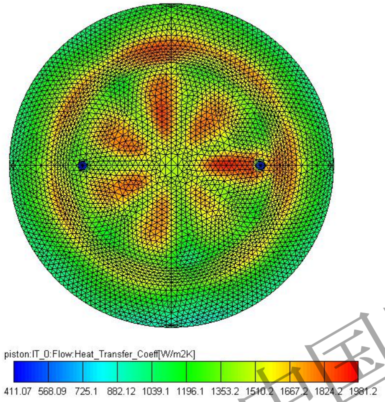
活塞动力学设计PISTON DYNAMICS

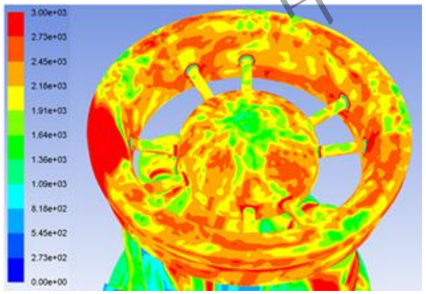
- □ **通过三维燃烧仿真，确定活塞热侧边界，通过振荡冷却分析，确定活塞冷却侧边界**

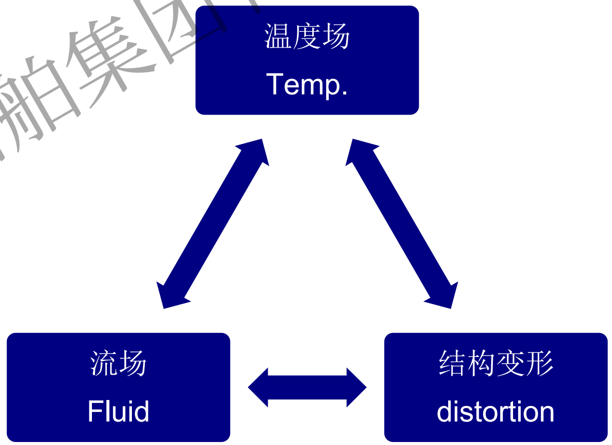
  Obtain boundary through piston shaker cooling simulation

- □ **根据热-机耦合分析，获得活塞变形和温度发布**

  Obtain piston temperature and distortion through thermal-structure analysis



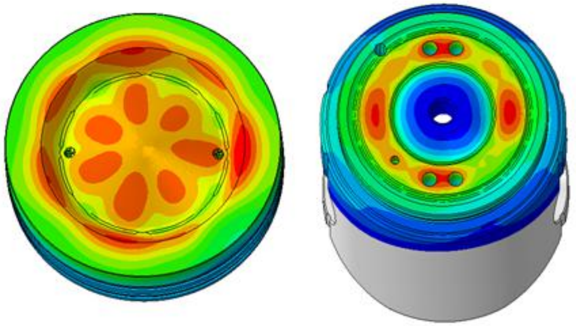


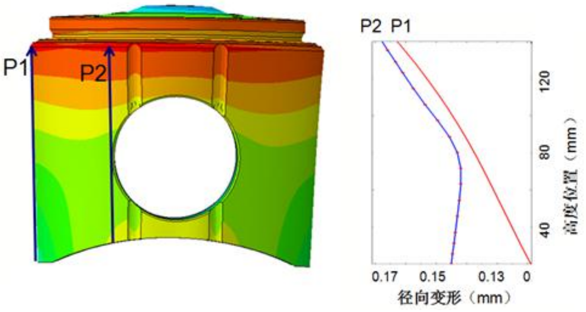


温度场
Temp.

流场
Fluid

结构变形
distortion

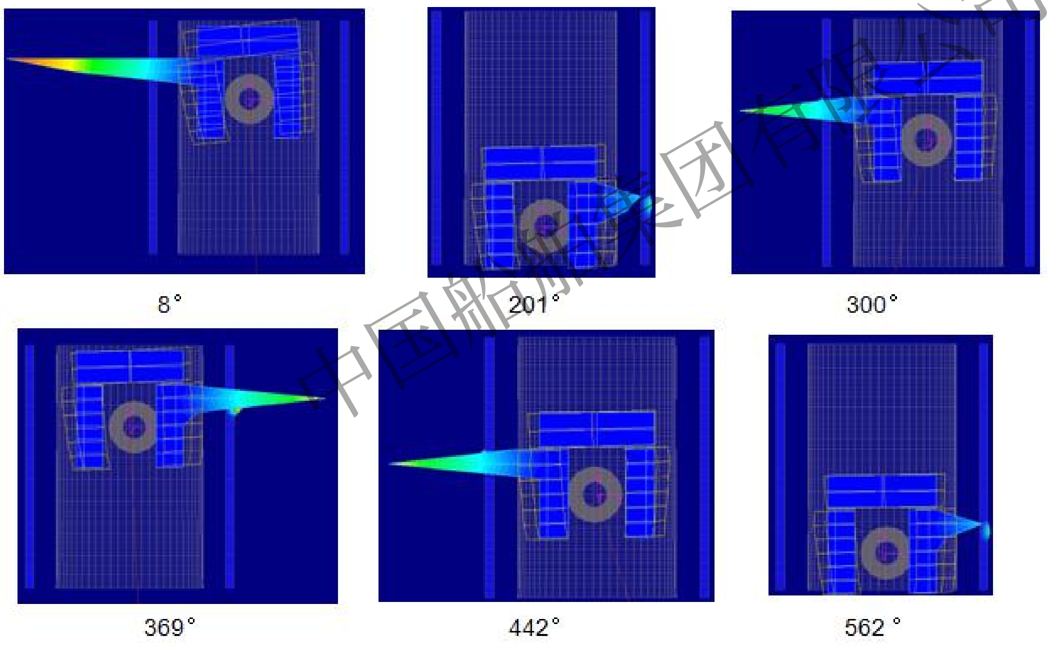




活塞动力学设计PISTON DYNAMICS

- □ **主推力侧存在三次敲击，最大敲击能量位于上止点处，行程中部存在两次较大敲击**

  Thrust side has three slap knock, the largest happens near the TDC, the other two happen at the mid-stroke



8°

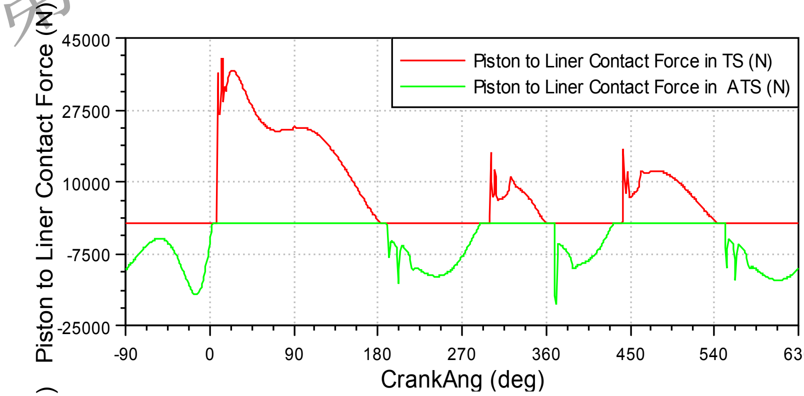
201°

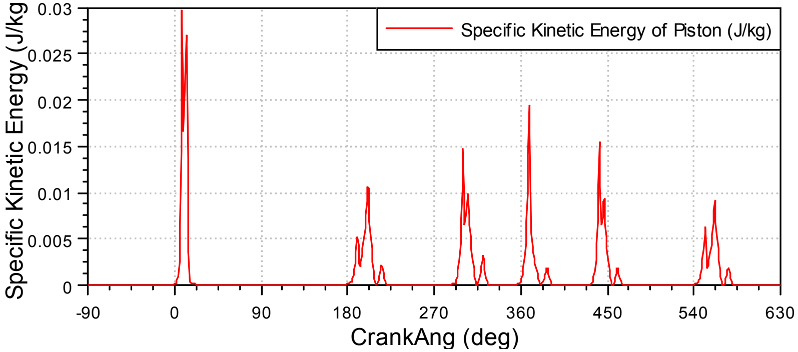
300°

369°

442°

562 °





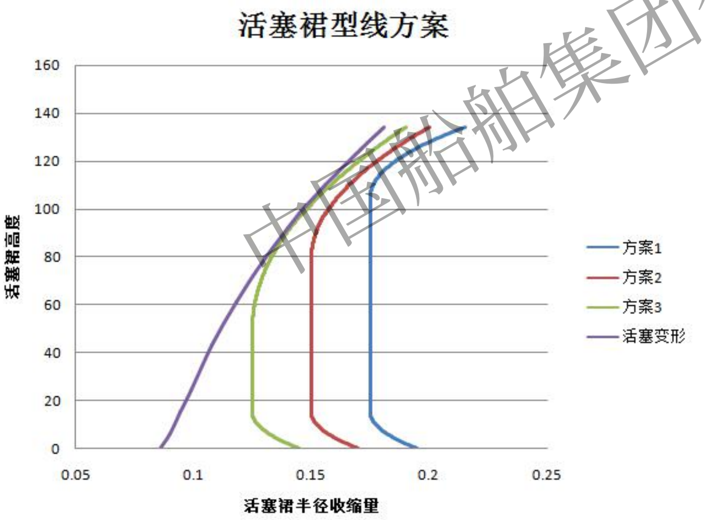
活塞动力学设计PISTON DYNAMICS

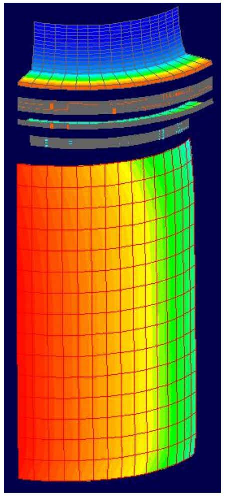
- 通过优化活塞设计，减小敲击力，提高气缸套抗穴蚀能力

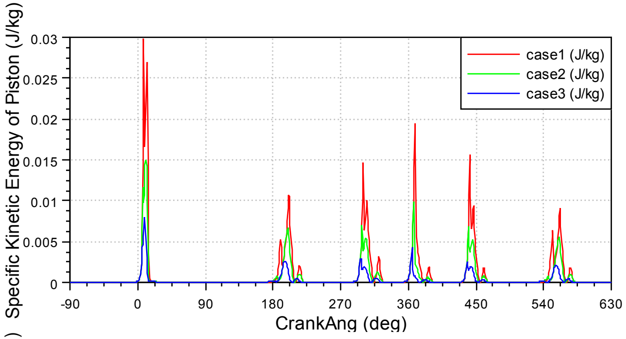
  Optimize to lower the slap force, increase the cavitation resistance

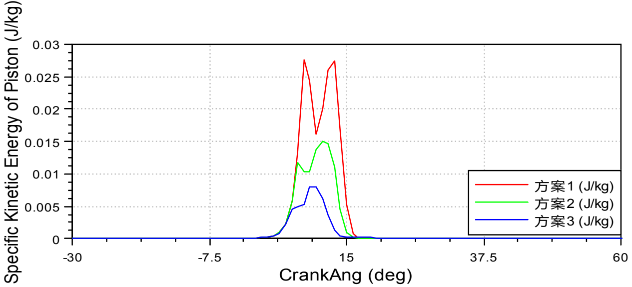
- 对比不同活塞裙型面，最大敲击能减小49.7%、73.2%，摩擦功略微增加~1%

  The kinetic energy reduced compared to the original skirt profile









03

气缸套振动

LINER VIBRATION

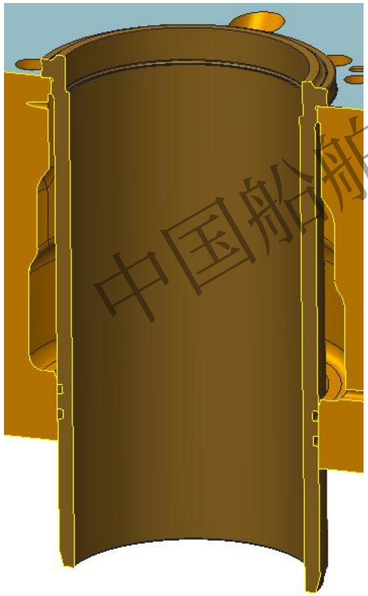
气缸套振动LINER VIBRATION

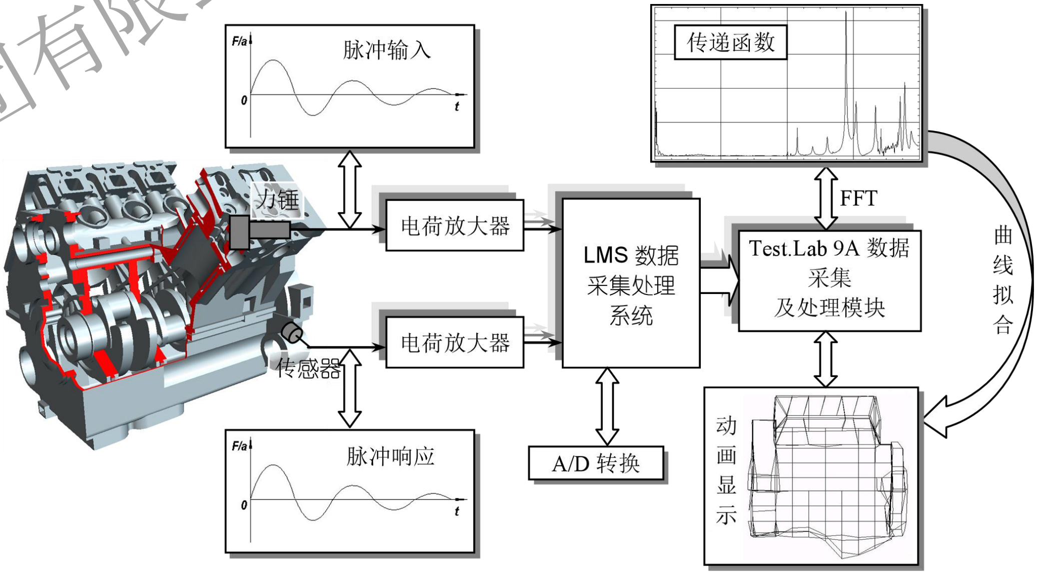
- **气缸套壁厚及支撑是影响振动的主要影响因素**

  Liner thickness and support distance is the main effects of liner vibration

- **运用锤击法脉冲激励SIMO对缸套进行模态测试，获取模态振型、固有频率等模态特性**

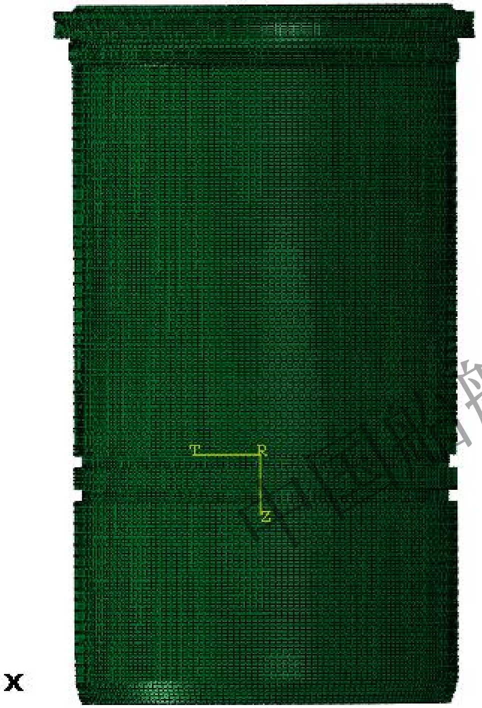
  Mode test to obtain the mode and frequency of liner

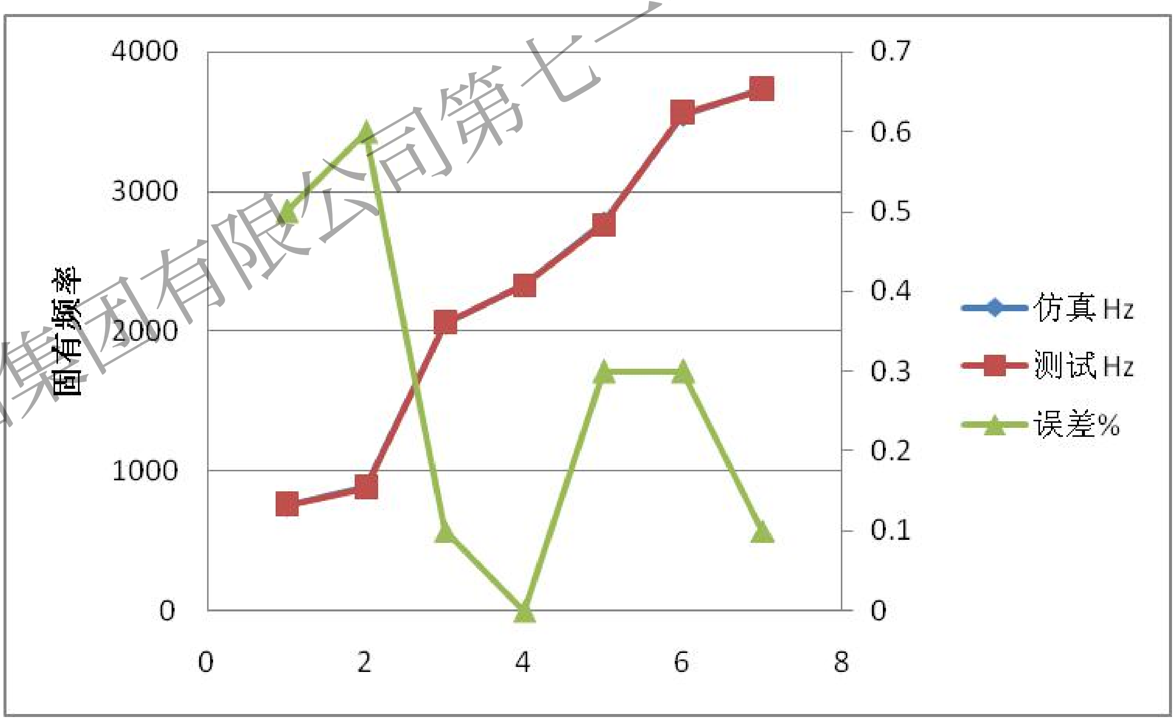




气缸套振动LINER VIBRATION

- **根据缸套模态特性的测试结果，修正仿真模型，误差小于1%**
  Calibrate the mode test and simulation model, the error is smaller than 1%





气缸套振动LINER VIBRATION

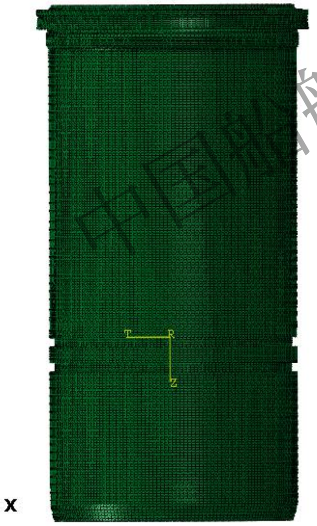
- ☐ **对比不同壁厚、支撑跨度对缸套模态影响**
  Compared influence of liner thickness and support distance on mode

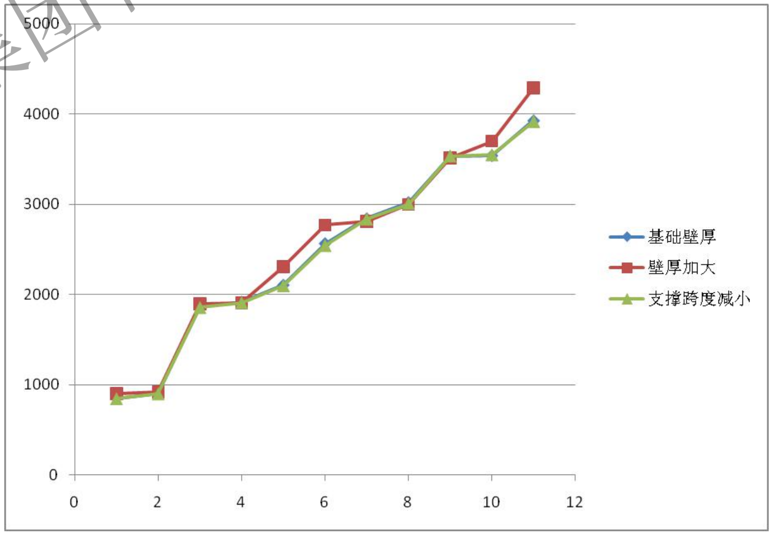
  - ➢ **增加壁厚，缸套整体刚度略有提升**

    Liner mode increased with increased thickness

  - ➢ **减小支撑跨度，模态结果略有下降，下降幅度不大**

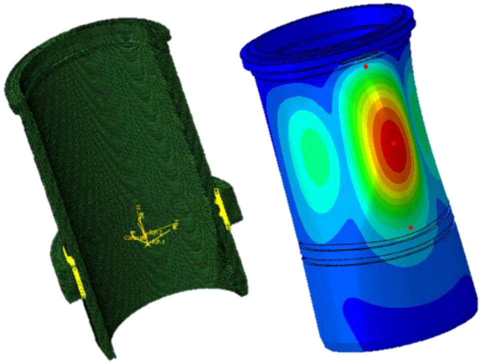
    Support distance has little influence on liner mode

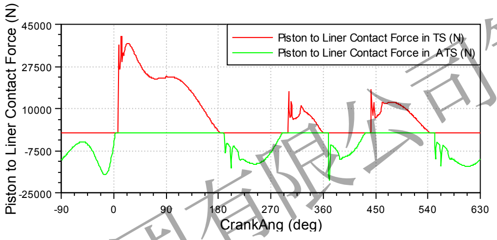


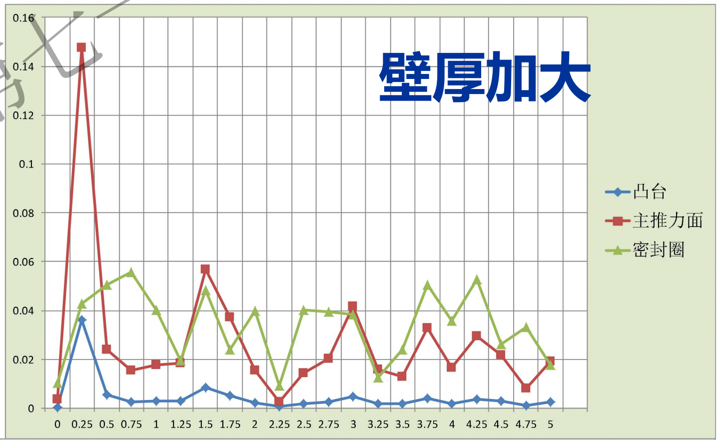


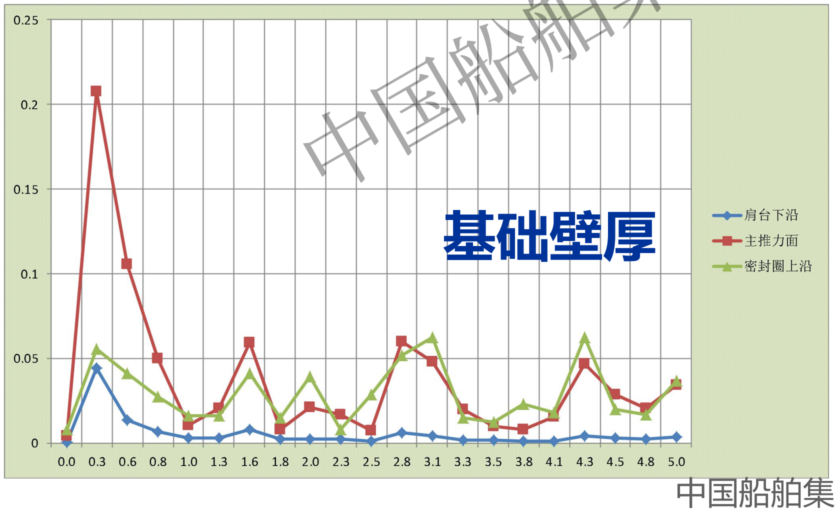
气缸套振动LINER VIBRATION

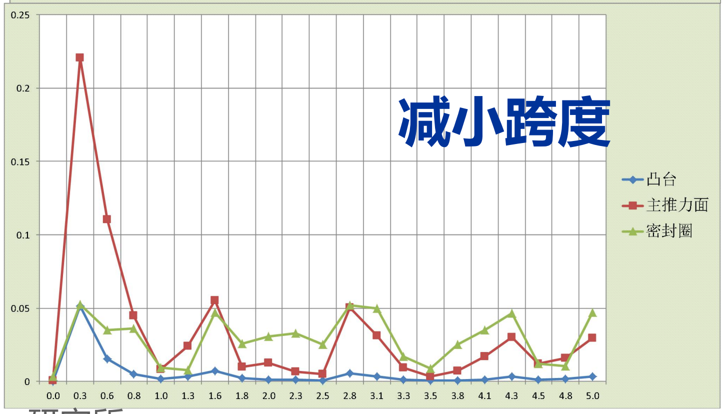
- □ **根据活塞动力学分析结果，开展气缸套振动响应分析**
  Liner vibration analysis with input from piston dynamics
- □ **对比不同壁厚、跨度对气缸套的振动响应影响**
  Compared influence of liner thickness and support distance on vibration






壁厚加大


基础壁厚


减小跨度

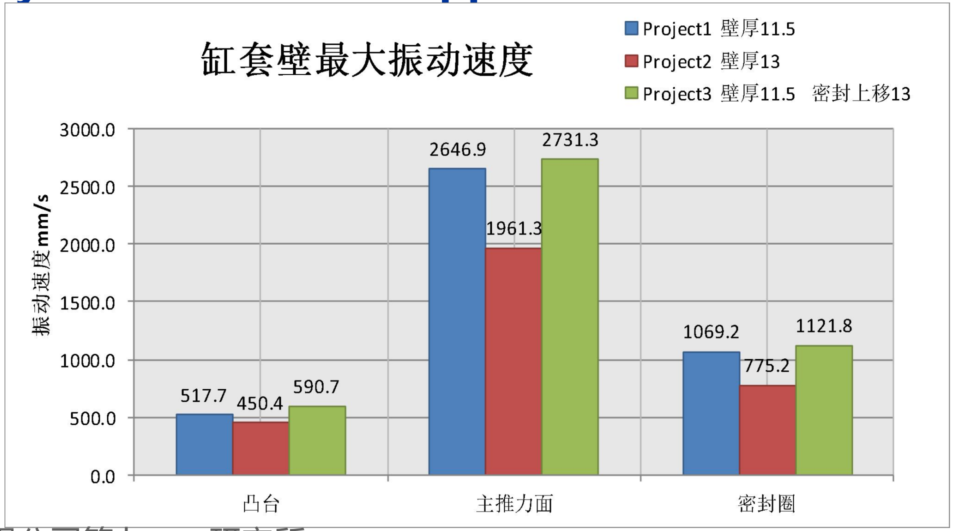
气缸套振动LINER VIBRATION

- **主推力面振动速度最大，密封圈位置次之，凸台位置处最小**

  Largest vibration velocity located at thrust mid-stroke
- **增加壁厚对表面振动速度衰减效果最好，振动速度下降了25.9%，综合考虑气缸套冷却，确定气缸套壁厚**

  Vibration velocity decreased 25.9% with increased liner thickness
- **减小跨度，振动速度上升~3%**

  Vibration velocity increased slightly with decreased support distance



04

冷却流动组织

FLUID DYNAMICS

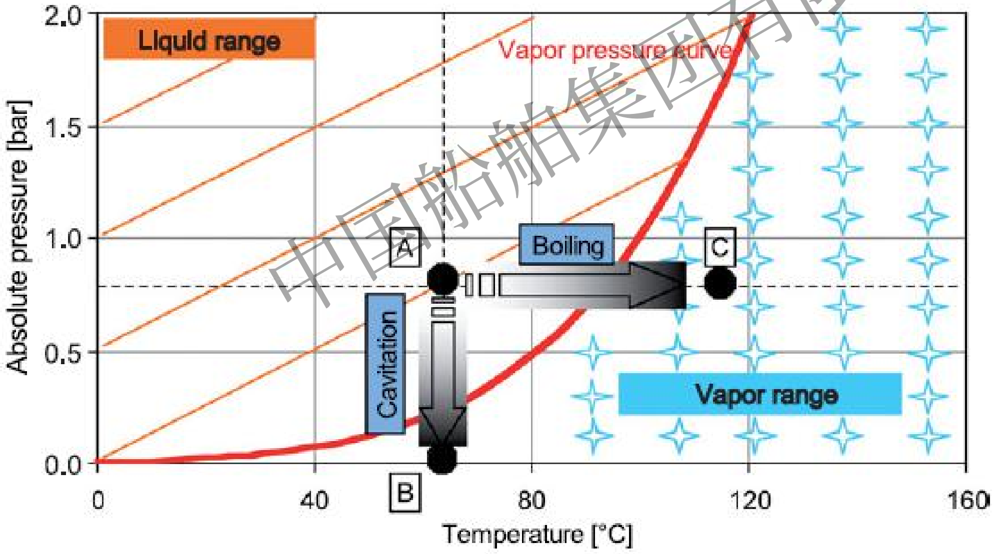
冷却流动组织 FLUID DYNAMICS

- □ **气泡生成倾向用空化系数表征，空化系数越小，越易产生气泡**

  Cavitation parameter to identify the tendency of cavitation

- □ **合理控制冷却液流场流速、压力，可降低穴蚀风险**

  Control fluid velocity、pressure to decreased cavitation

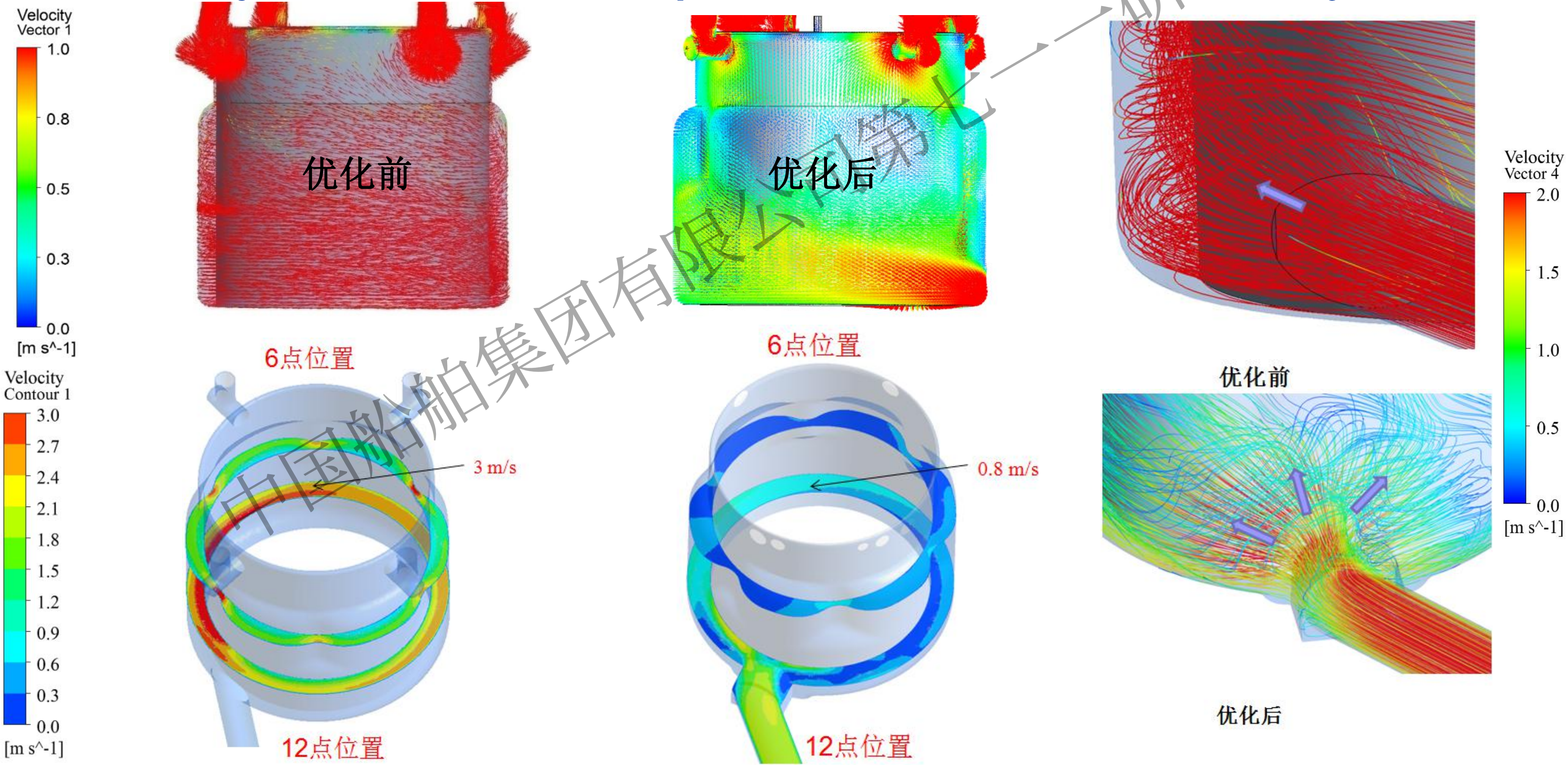


$$\sigma = \frac{p_{st} - p_v}{\frac{1}{2}\rho v^2}$$

pst:流体压力
pv: 空化压力
ρ：流体密度
v: 流体速度

冷却流动组织FLUID DYNAMICS

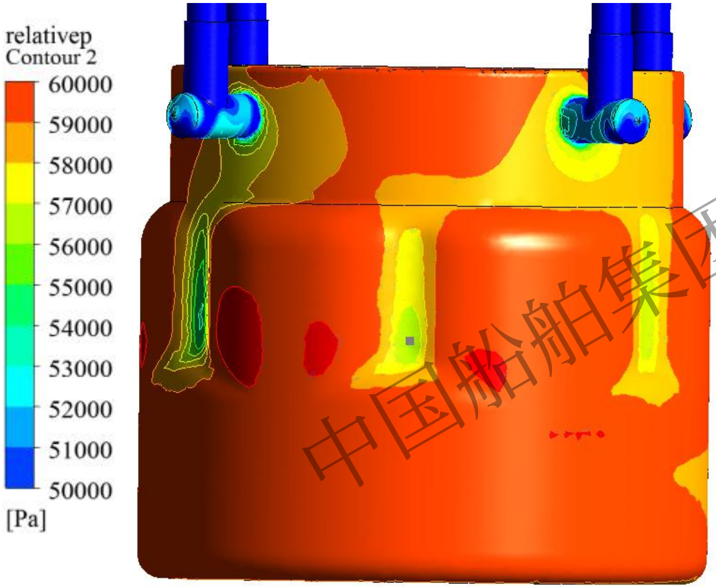
- **优化冷却腔水腔入口及截面，流速降低73%**
- **Velocity decreased 73% with optimized inlet and section of water jacket**



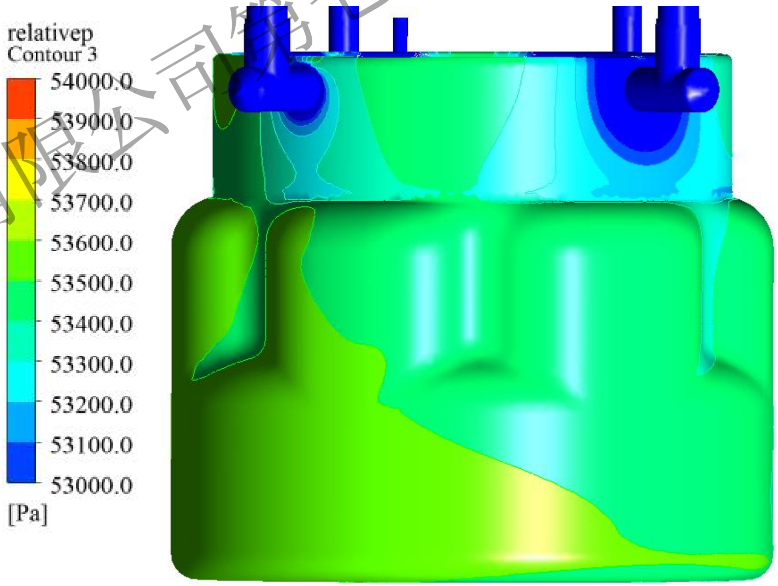
冷却流动组织FLUID DYNAMICS

- **优化后压力分布均匀**

  Little change on pressure, and pressure distribute even



优化前



优化后

试验验证TEST

- **经1000小时极限边界连续高负荷试验验证，无穴蚀现象**

  After 1000 hours high load test, none cavitation occurs

总结

- 综合采用活塞动力学设计减小振动激励源，优化缸套壁厚降低缸套振动速度，冷却流动组织，降低冷却流速的措施，气缸套设计经可靠性试验验证，未现穴蚀现象
- Through optimize piston dynamics, liner stiffness and fluid dynamics ,the liner pass the reliability test

谢谢！