Design and Test Demonstration of the JET01 Six-Stage High-Pressure Compressor

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ABSTRACT

This paper describes the results of a joint compressor research program, which was carried out by the Chinese Aviation Industry Corp. (AVICI and AVICII) and Rolls-Royce Deutschland Ltd. (RRD). The objective of the program was to design and test a modern six-stage high-pressure compressor with a comparatively high stage loading. The paper describes the aerodynamic design and the results of a rig test of the compressor in an atmospheric test facility.

The first part of the paper describes the improvements made to the available AVIC domestic design system, the verification of these improvements and of the available commercial design software. AVIC tools and commercial codes were adopted during the design phase. Secondly, the details of the aerodynamic design are presented. And finally, a comparison of predictions and test results of the six-stage test-rig are shown.

NOMENCLATURE

π_t	total pressure ratio
π_{max}	maximum pressure ratio
η_{ad}	adiabatic efficiency
SM	surge margin
V_t	tip radius tangential speed of the 1st rotor
M_{in}	mass flow at the inlet
M	mass flow

INTRODUCTION

In 1999, a research program to develop a high-pressure compressor for a commercial engine application was agreed between AVIC and RRD. Subsequently a Joint Engineering Team (JET) was established to deliver the program. To meet the objective of the program, the task was structured in three phases:

Phase I: Validation of the compressor design codes to be used by AVICI, validation of available commercial codes and set up of an Integrated Design System (IDS) using the best tools.

Phase II: Design of a six-stage HP compressor (named JET01 HP compressor) on the basis of an existing seven-stage compressor developed by the Chinese Gas Turbine Establishment (GTE). Manufacture and test an aerodynamic test-rig to demonstrate performance.

Phase III: Design of an engine-worthy HP compressor with commercial application potential.

So far, the first two phases were completed successfully.

VALIDATION OF SOFTWARE AND SET-UP OF IDS

The first step of the JET program was to validate the AVIC compressor design codes. The following procedure was used: JET engineers carried out the validation calculation with AVIC tools on agreed test cases. Results were reported and submitted to the JET team in RRD, which compared the data to results of established tools.

At the end of phase one, AVIC engineers

completed the validation calculation for all software necessary to design the HP compressor, which covers the aspects of aerodynamics, heat transfer, strength and vibration etc.

The validated results demonstrated that deviations of calculation result of most AVIC tools were within the engineering accuracy compared with results from similar software used by RRD. For example, the S1 stream surface calculations are shown in figure 1, 3D CFD analysis with commercial software is depicted in figure 2. There were also some deviations, such as flow angles from the through-flow design software, which exceeded the engineering accuracy.

The airflow angle deviation obtained from the original through-flow calculation is shown in figure 3. Obviously there is a large deviation in the results between the AVIC through-flow program and the RRD through-flow calculation. After analyzing in detail, it was found that the deviation was mainly caused by the use of an unsuitable specific-heat-capacity-ratio function. The two points jumping in figure 3 just correspond to different specific-heat-capacity-ratio values, this was caused by a discontinuity of the respective function. Therefore, the calculation method for the specific-heat-capacity-ratio was modified by the use of a seventh order polynomial function. The through-flow calculation domain and the calculation stations were set identical to the through-flow model of RRD in the following calculation. The calculation results for airflow angles using the improved through-flow analysis code are compared in figure 4. It can be seen that after the improvements the angle deviation of the AVIC through-flow tool is now within the engineering accuracy.

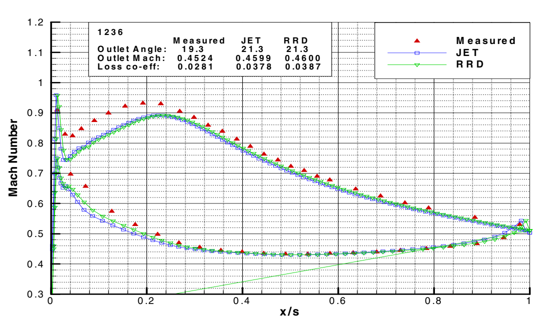


Fig. 1: Validation comparison for S1 stream-surface

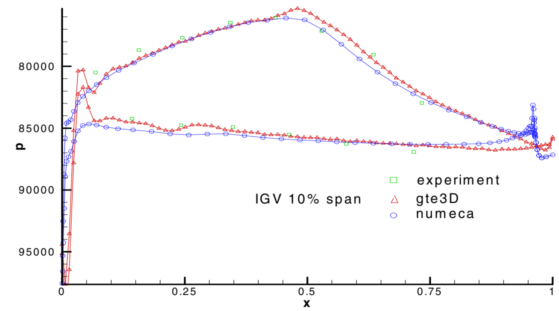


Fig. 2: 3D CFD validation

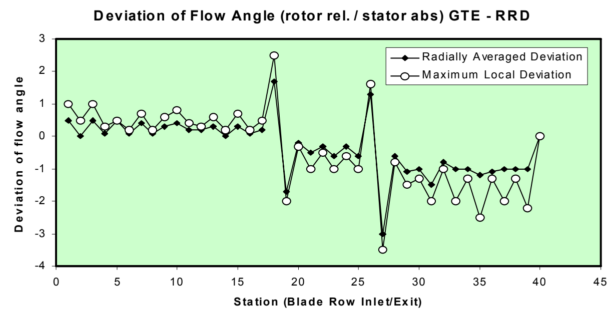


Fig. 3: Preliminary validation result of the JET through-flow

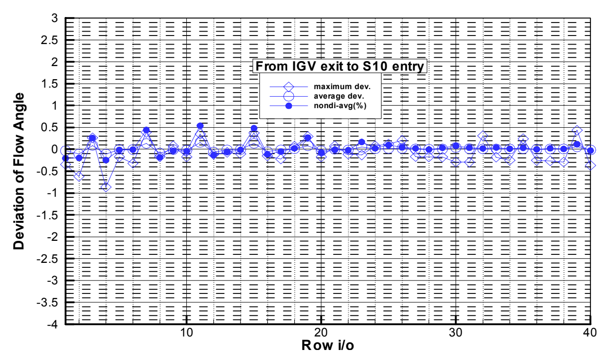


Fig. 4: Validated result for the improved through-flow

After the completion of the tool validation an IDS system for the JET program was set up in the JET office located in Beijing. Based on the verified results it was decided to carry out the aerodynamic design with AVIC tools (partly improved), augmented with the commercial FineTurbo Numeca 3D CFD tool. The Unigraphics 3D-CAD software in combination with a PDM system was chosen to carry out the mechanical design. For stress analysis a commercial FEM software tool was selected. This first phase was completed in 2002.

BASELINE SEVEN-STAGE COMPRESSOR

The JET01 six-stage HP compressor was designed based on a seven-stage research HP compressor developed by GTE [1]. The baseline compressor was designed at the end of the 1980’s. Its main design parameters are shown in table 1.

Tab. 1: Main design parameters of the seven-stage compressor

π_t	η_{ad}	M_{in} (kg/s)	SM	V_t (m/sec)
7.02	0.84	17.64	≥17%	384.5

General Design Rules for the Aerodynamic Design

1. To achieve the surge margin goal, the design pressure ratio was increased over the nominal compressor pressure ratio.
2. For minimum shock and profile losses the relative Mach numbers on blades and vanes were designed as low as possible. Therefore, low Mach numbers and high blade loading characterize the seven-stage compressor.
3. To prevent high mixing losses the total pressure of the airflow at each stage outlet was designed to be uniform along the span.

Design Features of the Annulus

1. To maintain tight tip clearances in the rear of the compressor, the last two stages were designed with a straight inner flow path.
2. The radius of the inner wall increases smoothly from the inlet through 5 stages.
3. To control the aerodynamic loading of the blade tips, the radius of the outer wall was gradually decreased.

The annulus of the seven-stage compressor is shown in figure 5.

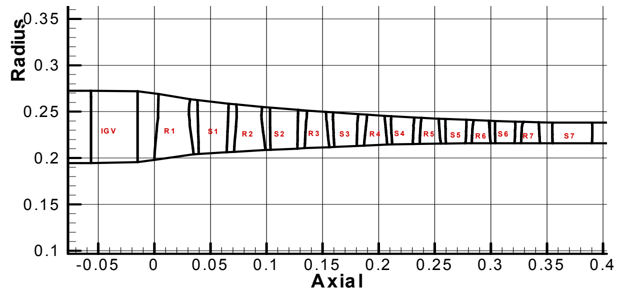


Fig. 5: Annulus diagram of the seven-stage compressor

Airfoil Design Features

1. A NACA65 profile was used for the inlet guide vane and the first-stage stator vane.
2. Due to the relative Mach number of the front stage blade tips being greater than 1.0, a pre-compression multi-arc profile was used here to reduce the shock loss.
3. A rear-cambered multi-arc profile with larger camber ratio was used for the rear stage rotor tips in order to improve the turbulent flow at the end wall corner.
4. A near double-circular-arc airfoil was used for rotor hub to control the airflow at inlet and outlet.
5. Double-circular-arc profiles were used for the front stage stators and a forward-cambered multi-arc profile was used for the rear stage stators to reduce the effect of the end wall and the impact of secondary flow.
6. The critical area ratio of minimum throat for each stage was strictly controlled; the values are gradually increasing stage by stage.

The rotor of the seven-stage compressor is shown in figure 6.

Fig. 6: Rotor of the seven-stage compressor

Test Results

The compressor was tested in GTE's compressor test bed around 1990. The experimental results showed that the performance of the compressor met the design target of 83,9% adiabatic efficiency and 26% of surge margin at design speed. The test results at the design point are detailed in table 2.

Tab. 2: Test results of seven-stage HPC at the design point

Parameter	Test value
M_{in} (kg/s)	18.05
π_t	7.02
η_{ad}	0.839
SM	26%

AERODYNAMIC DESIGN OF THE JET01 HP COMPRESSOR

Summary of the Aerodynamic Design

The JET01 compressor was designed on the basis of the baseline seven-stage compressor with one stage reduced. The corrected mass flow rate & total pressure ratio was kept unchanged. The adiabatic efficiency target was increased from 84% to 85%. The design parameters are shown in table 3.

Tab. 3: Design parameters of the JET01 compressor

Parameter	Value	Unit
π_t	7.02	
M_{in} (kg/s)	17.64	kg/s
η_{ad}	≥0.85	
SM	≥20%	

The aerodynamic design was carried out in the following sequence: 1D mean-line design, through-flow design, blading, S1 stream surface analysis, full-3D analysis and compressor map prediction using 1D and 3D methods.

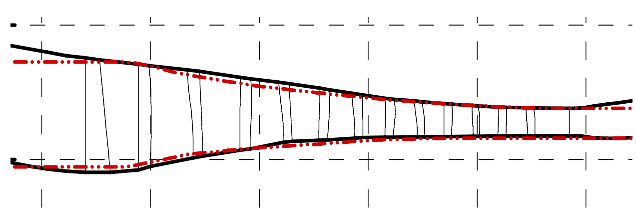
1D Mean-Line Design

The 1D mean-line calculation code used by AVICI can be applied in two modes: design mode and prediction mode. In the design mode mean-line velocity vectors and loading parameters are generated. In the prediction mode stage characteristics based on geometry input and correlations are calculated which are stacked up subsequently. The code also can also provide the characteristics for each corrected speed with the use of a VSV schedule optimization.

The flow path for JET01 compressor was modified relative to that of the original seven-stage compressor. Two constraints for the flow path had to be assumed:

1. The inlet blade tip radius of the first stage rotor had to remain unchanged.
2. The outlet radius of the casing had to remain unchanged.

In order to decrease the loading of each stage higher blade tangential speed than on the 7-stage design was used. During the 1D preliminary design the flow path shape was optimized within the given constraints. The influence of the flow path of the pre-diffuser and of the intermediate casing on to the HPC inlet and exit conditions was separately considered. The optimized JET01 HPC flow path is shown in comparison to the baseline seven-stage compressor in figure 7.



Solid: JET01 HPC

Dash-Dot: Original Seven-Stage Compressor

Fig. 7: Flow path comparison of baseline and JET01 HPC

For the design of the JET01 compressor, the same basic design principles as for the seven-stage compressor were used. In the design through-flow the total pressure ratio was increased over the nominal design pressure ratio by 4.33%, i.e., a total pressure ratio of 7.324 was used. During the design optimization, the distribution of the final stage pressure ratio was fixed for each stage. The average stage parameters obtained from the 1D design are listed in table 4.

Tab. 4: 1D average stage parameters

Stage No.	Loading coefficient	Flow factor	Diffusion factor	
			Rotor	Stator
1	0.333	0.378	0.498	0.455
2	0.348	0.436	0.491	0.497
3	0.362	0.477	0.482	0.453
4	0.364	0.516	0.458	0.429
5	0.354	0.469	0.455	0.492
6	0.350	0.450	0.454	0.523

Mean-line-prediction of compressor performance is shown in figure 8. It shows that the surge margin could be reached at design speed and that there is also sufficient surge margin at off-design speeds. The maximum efficiency at design speed exceeds 0.85; peak efficiency is predicted at 90% corrected speed.

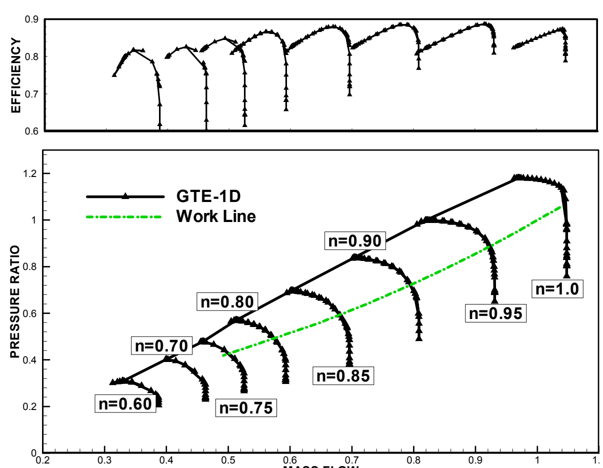


Fig. 8: JET01 HPC, mean-line prediction

Through-Flow Design

The through-flow aerodynamic design was carried out on the basis of the 1D mean-line design. For the through-flow calculation the improved streamline curvature code was used, which adopted the improved specific-heat-capacity-ratio, verified in the first phase of the JET work. For the through-flow calculation it was assumed that the airflow was inviscid, adiabatic and steady. By using a blockage factor in the calculation, end wall boundary layer effects on axial velocities were considered. The through-flow model contained the swan-necked duct in the front of the JET01 6-stage compressor. This duct connects the HPC flow-path to the LP compressor. The effects of the intermediate casing duct were taken into account in the through-flow design.

During the design of the JET01 compressor, the blockage factor distribution was derived from a correlation. The axial blockage distribution selected for this compressor is shown in figure 9 (red color). The blockage factor (green color) of the original 7-stage compressor is also shown in the figure for comparison. It can be seen that the magnitude of blockage for both compressors is not too different. Larger differences mainly occur in the middle of the HPC. This is caused by the more linear distribution used for the original seven-stage compressor. In the new six-stage design the blockage was increased gradually in the front stages and more rapidly through the rear stages.

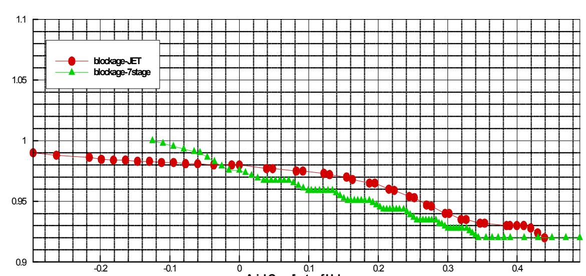


Fig. 9: Comparison of blockage factor distributions

Axial gapping of the blade rows is an important part of the through-flow design. To reduce blade forcing of upstream and downstream blade/vane rows, axial gaps were adequately widened. The final calculation of the blade forcing, using the final axial clearance, demonstrated that the axial clearance between the blades rows of the JET01 HPC fully meets the requirements for safe compressor operation.

During the design iterations some suggestions to improve the meridional aerodynamic layout were put forward by the independent review team:

1. The axial distance between the inlet guide vane and the struts of the swan-necked duct was too close.

2. The AVDR at the hub of the first rotor calculated in the preliminary though-flow was high; this off-loaded the R1 hub section and up-loaded the hub sections of the following stator vanes and rotor blades. Therefore the inner flow path of the first rotor in the through-flow model was lowered to reduce the AVDR value. This allowed AVDR values of the second and third rotors to be increased and hub loading to be reduced.

The final meridional flow path of the JET01 compressor is shown in figure 10.

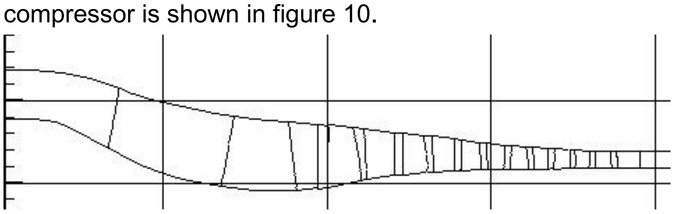


Fig. 10: Meridional flow path of the JET01 6-stage HPC

Some results of the through-flow design are shown in figures 11 to 15.

The relative inlet Mach number of the rotor blades is shown in figure 11. It can be seen that the relative tip Mach number of the first rotor was limited in the range of 1.1 to 1.2. This allowed designing a transonic blade with high pressure rise capability at high efficiency.

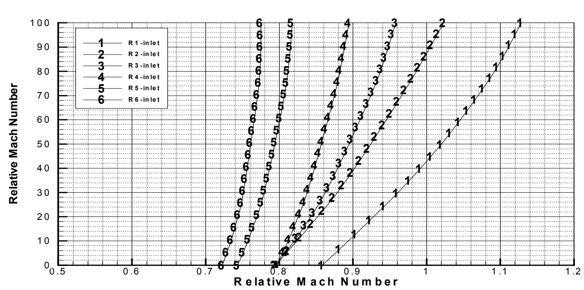


Fig. 11: Relative Mach number distribution of rotors

The span-wise distributions of diffusion factors are shown separately for rotors and stators in figures 12 and 13. Different criteria for maximum diffusion factors of rotors and stators were used. Average diffusion factor of rotor blades had to be lower than 0.55, and lower than 0.6 for stators. During design iterations, diffusion factors were balanced stage-wise and minimized by appropriate selection of design parameters.

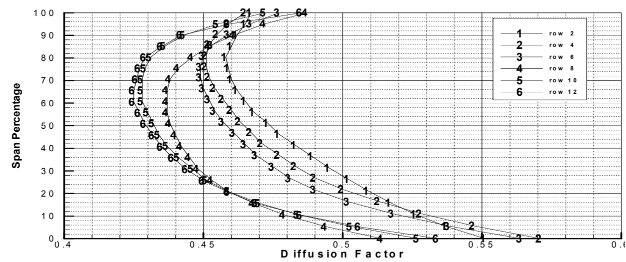


Fig. 12: Diffusion factor distribution of rotors

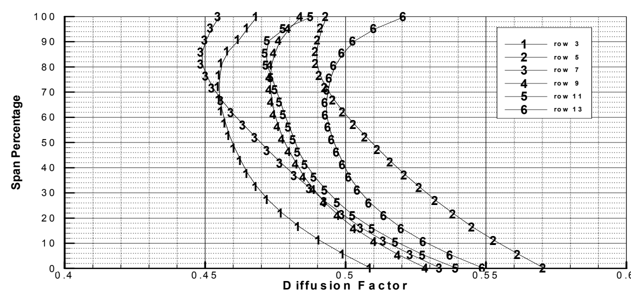


Fig. 13: Diffusion factor distribution of stators

Figures 14 and 15 depict the De-Haller number distributions of rotors and stators respectively. The criterion used in the design of the JET01 HPC is that De-Haller number of all blades have to be greater than 0.6.

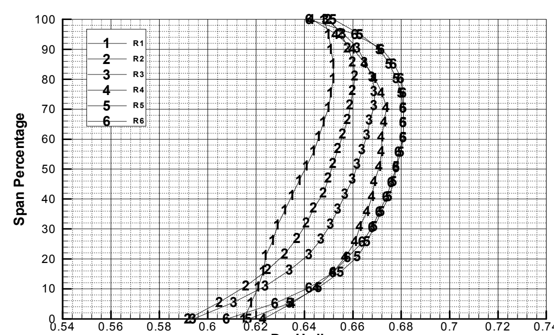


Fig. 14: De-Haller number distribution of rotors

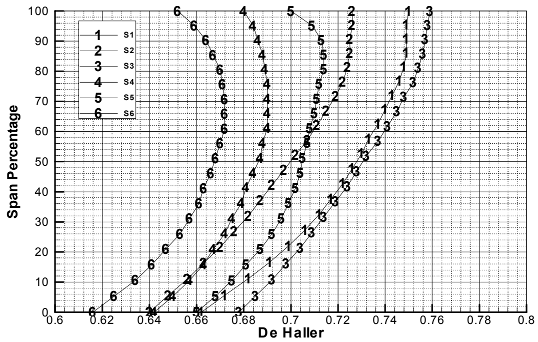


Fig. 15: De-Haller number distribution of stators

The through-flow input was updated iteratively during the blading design based on the results of the blade-to-blade calculations. The final solution had all updates from the final blading incorporated.

Blading and Blade-to-Blade Stream-Surface Analysis

All blades were designed using the GTE customized airfoil method with elliptical leading edges. The results of blade-to-blade calculations and full-3D analysis were used to set incidence angles and deviation angles. Some design parameters, such as the relative maximum thickness, the location of maximum thickness, were used to tune blade vibration frequencies to fulfill resonance criteria. All rotors were designed with some forward sweep. Figure 16 shows the UG solid model of the first rotor blade of JET01.

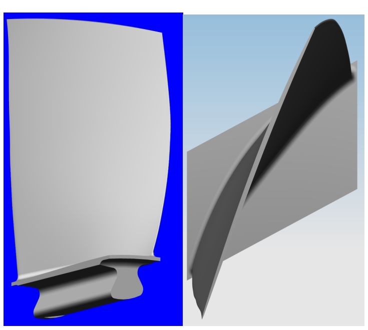


Fig. 16: The UG solid of the 1st rotor

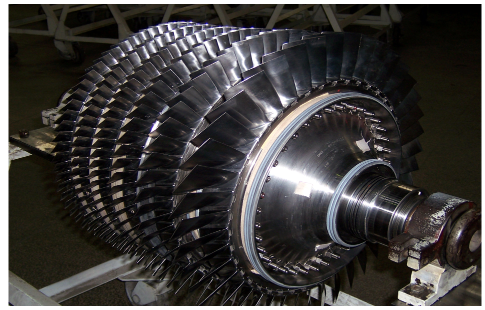


Fig. 17: The rotor component assembly

The blade-to-blade analysis of typical sections of some JET01 blades is shown in figures 18 to 21. The optimized design, avoids separations on the suction surface effectively.

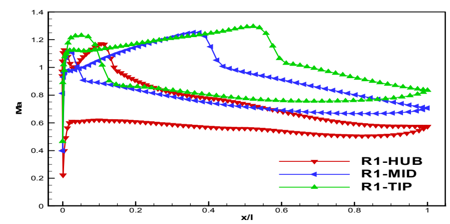


Fig. 18: Mach number distribution of the 1st rotor

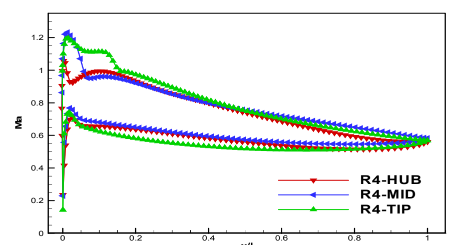


Fig. 19: Mach number distribution of the 4th rotor

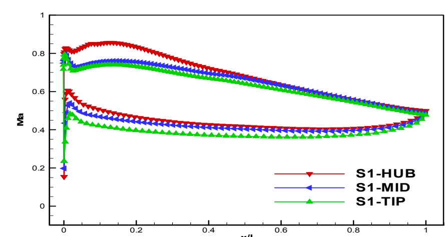


Fig. 20: Mach number distribution of the 1st stator

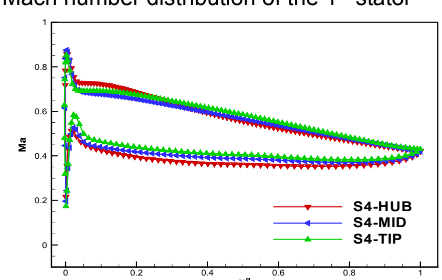


Fig. 21: Mach number distribution of the 4th stator

Figures 22 and 23 show the total pressure loss coefficient against inlet flow angle of typical sections for stators 3 and 4 respectively. It can be seen that the blade loss is low and suitable incidence margin is available.

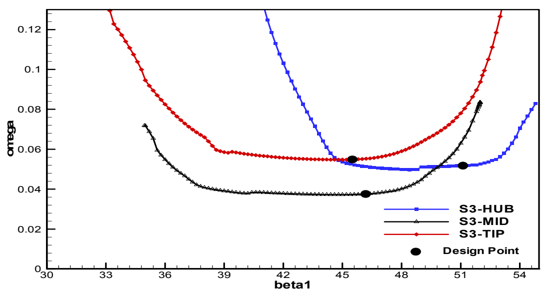


Fig. 22: Pressure loss coefficient vs. inlet flow angle, 3rd stator

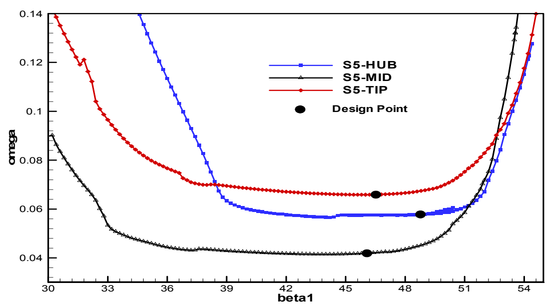
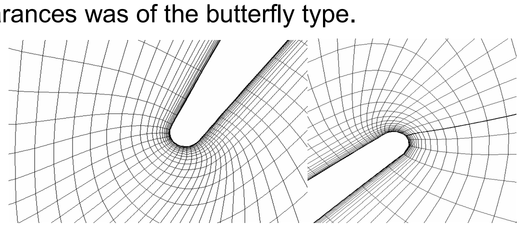


Fig. 23: Pressure loss coefficient vs. inlet flow angle, 4th stator

<u>Full-3D Analysis</u>

Two 3D-NS analysis codes were applied in the design of the JET01 HPC. One was GTE's viscous 3D finite volume code. The other one was the commercial FineTurbo NUMECA code. Since the GTE code is less effective in multi-stage conditions the NUMECA code was chosen as primary tool.

An O-type mesh was used for the airfoils in the NUMECA calculation for better grid quality at the edges as shown in figure 24. The tip clearance of rotor blades was set to 0.2 mm. The 4th and 5th stators adopted cantilever blades and the clearance between hub and blades was also set to 0.2 mm. The grid used in the clearances was of the butterfly type.



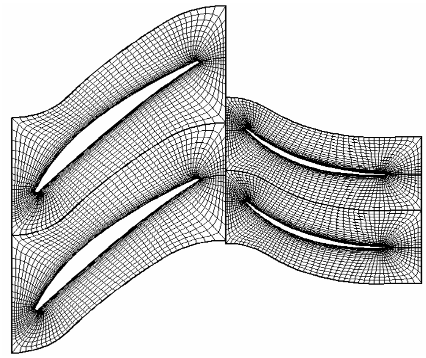


Fig. 24: Grid of full-3D calculation

The resulting performance at the design point compared to through-flow results is listed in table 5. The resulting flow field is shown in figures 25 and 26. It can be seen that there is some flow separation at the root of the 6th rotor.

Tab. 5: Predicted performance 3D vs. through-flow

Parameter	M (kg/s)	π_t	η_{ad}
Through-flow	17.64	7.326	0.8426
3D	18.76	7.315	0.849
Relative deviation	6.35%	0.15%	0.76%

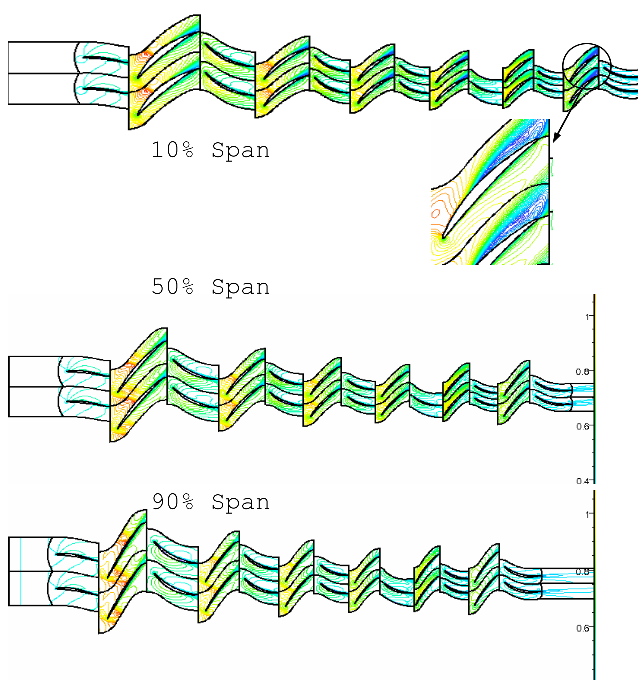


Fig. 25: Flow field blade-to-blade

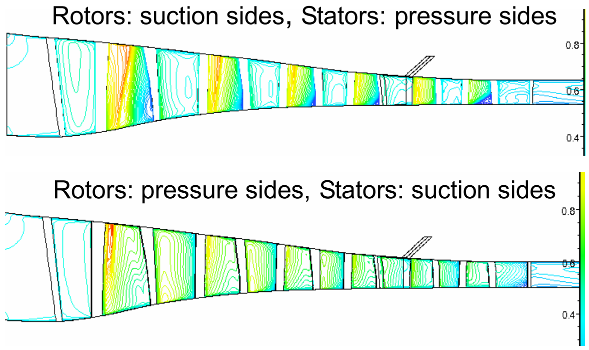


Fig. 26: Flow field meridional section

The map of the JET01 HPC predicted by NUMECA is plotted in figure 27. It covers the corrected speed range from 80% to 100%. Both, coarse grid (Multi-grid level: 111) and refined grid (Multi-grid level: 000) have been used to predict the 100% characteristic. The predicted surge margin was 18.7% and 19.0% respectively. The grid effect on efficiency was more dominant, using the refined grid efficiency was 1% higher. The characteristics of the other speeds were all calculated with the coarse grid. The results of the 3D calculation showed that the performance of the JET01 HPC would achieve the design objective.

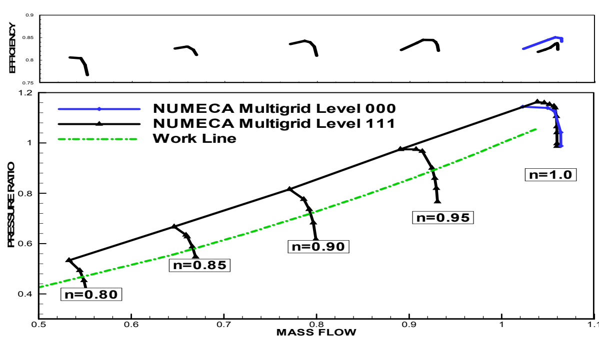


Fig. 27: Map of JET01 HPC predicted by NUMECA

JET01 HPC EXPERIMENT AND TEST RESULTS

The JET01 six-stage compressor rig was tested at GTE's compressor test facility. The bed is an open throttle facility driven by a power turbine. The whole arrangement consists of a venturi for mass flow measurements, inlet throttle valve, diffuser, flow straightener, bleed system, gearbox, exhaust duct and power turbine. The rotational speed is adjusted by controlling the airflow to the power turbine. The facility's general arrangement is shown in figure 28.

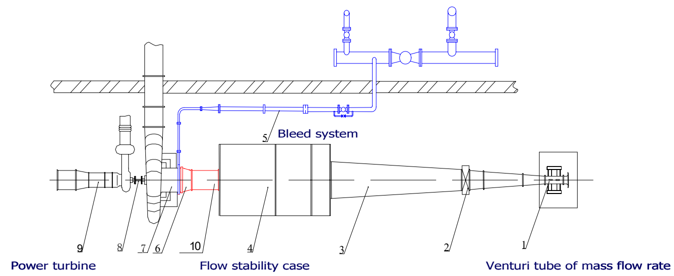


Fig. 28: General arrangement of the GTE test facility

After completion of parts manufacturing and assembly, the JET01 HPC rig was successfully tested at GTE's test facility. The following data was recorded:

1. Characteristics including surge points using both the design VSV schedule and an optimized VSV schedule at relative corrected speeds of $\overline{n} = 0.60$, 0.70, 0.75, 0.80, 0.90, 0.95 and 1.00.
2. Inlet and exit pressures/temperatures at various radial and circumferential positions for above test points.
3. Static pressures at inner/outer wall at rig inlet and outlet. Inter stage static pressures along outer wall.
4. Dynamic pressures at rig inlet, outlet and behind each rotor.
5. Dynamic stresses on the rotors 1 and 2.

The characteristics of the baseline HPC and the JET01 HPC are plotted in figure 29. The measured surge margin of the JET01 HPC is larger than on the seven-stage compressor, especially at $\overline{n} = 0.60$~0.90. The efficiency of the JET01 HPC at design speed is 1.2% higher. At part speed, the efficiency of JET01 slightly lower than that of the seven-stage compressor and could be optimized by adjusting the VSV schedule.

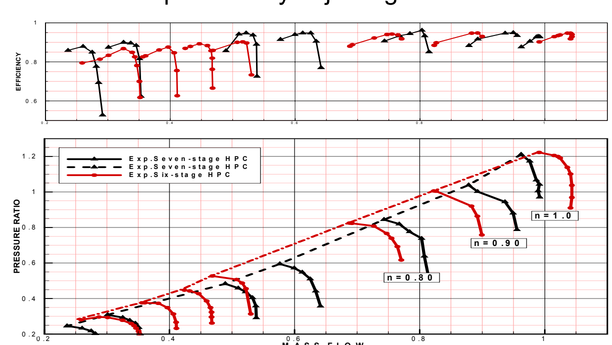


Fig. 29: Characteristics of the JET01 and seven-stage HPC

A performance overview of the baseline seven-stage compressor and the JET01 HPC at design speed is listed in table 6. The JET01 HPC achieves its design goals. Efficiency at the design point is 1.2% higher than that of the seven-stage compressor.

Tab. 6: Comparison of test results at design speed

Parameter	JET01 Design	Baseline Experiments	JET01 Experiments
M (kg/s)	17.64	18.0	18.78
π_{max}		8.46	8.58
η_{ad}	85%	84%	85.2%
SM	18%	25%	28.66%

Figure 30 shows the comparison of test data and prediction of the JET01 HPC map. It can be seen that the surge margin prediction by NUMECA is lower than the experimental results; the deviation grows with speed. At high speed ($\overline{n}=0.95$, $\overline{n}=1.00$), the predicted mass flow is very close to the experimental results. The results with the refined grid match the test result even better. The maximum pressure ratio predicted by NUMECA is lower than tested; at design speed it has a 5% deviation from the test results. The efficiency calculated with a coarse grid is lower than the experimental results, but the trend is close, especially at high speed. At design speed, the efficiency and its trend predicted with the refined grid are both close to experimental results.

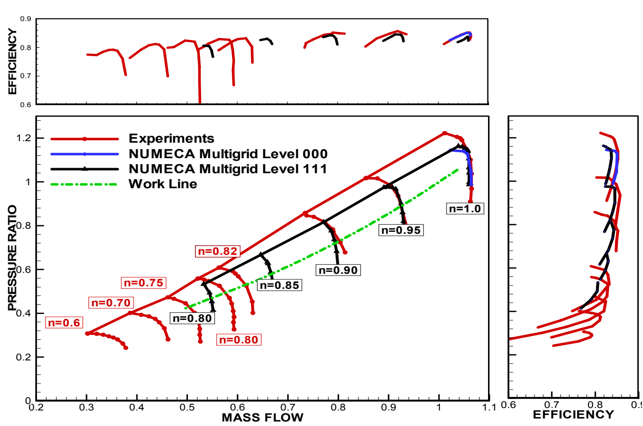


Fig. 30: Comparison of JET01 experiment results and NUMECA full-3D prediction

CONCLUSIONS

1. A modern high-pressure compressor was designed and tested. The test results demonstrate that the JET01 HPC met all design targets (efficiency, flow, surge margin) in the first attempt.

2. The technical success of the JET01 HPC emphasizes that AVIC's compressor design system has achieved maturity and reliability. It proves the design capability of the organization and marks a milestone for China's evolving civil engine design capability.

3. The JET01 HPC project is based on the successful cooperation between AVIC and RRD.

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