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# A Booster Stage with Tandem Cascade Rotor for Fan Engine

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## ABSTRACT

Booster stages for high bypass fan engines must operate under relatively low rotational speed due to the restriction on the fan rotor tip speed for keeping high efficiency of fan rotor blade, and, conventionally, multi-stage configurations are used in order to increase loading of the booster.

In this study, an alternative way to increase loading of the booster stages by applying tandem cascade rotor blade was examined. A booster stage with tandem cascade rotor blade was designed and tested in order to evaluate the basic performance and applicability of tandem cascades to fan booster stages.

The overall performance of the rotational rig tests at several speeds were measured and the results showed the satisfactory basic performance such as the efficiency and surge margin of the tandem cascade booster stage.


## INTRODUCTION

### Tandem Cascade Concept

Tandem cascade is a set of two separate cascades arranged in series with small gaps and be able to reduce boundary layer growth by blowing energized flow from front cascade to suction surface of rear cascade. So, potentially, tandem cascades may be used to increase loading and efficiency, and additionally be able to simplify the configuration and save the weight by reducing the required number of stages compared with multi-stage configuration of conventional cascades. And, so far, design and experimental results on tandem cascades have been reported by other authors such as Bammert et al (1979,1980) and Guochan et al (1985).

### Application to booster stages

The booster stages of high bypass ratio fan engines must be operated under fairly lower rotational speed compared with standalone compressors of similar specifications.

It is due to the fact that fan rotor tip radius and the number of rotations of LP spool is chosen, to keep high engine overall efficiency, so that it produces the adequate fan rotor tip speed for maximizing the performance of the fan rotor, while the tip radius of the booster stages are determined from bypass ratio.

And, as the booster stages rotate with the same number of rotations as the fan rotor blade but with considerably smaller tip radius compared with fan rotor , the rotational speed of the booster stages are not necessary suitable to produce sufficient amount of loading per stage.

So, multi-stage configurations are often used for booster stages when high loading are required. But it implies increase of the structural complexity and weight.

While, it is anticipated that applying the tandem cascades for rotor blades of fan booster stages would compensate the inherent low loading characteristics of the conventional booster rotors by providing higher loading per stage with efficient two rotating cascades in series, under the relatively low rotational speed, than the conventional cascades, and also reduce the weight of fan module by simplified configuration and reduced axial arrangement length through the reduction of number of stages.

## DESIGN

For designing the booster stage, a virtual high bypass ratio fan engine with corrected mass flow and bypass ratio of around 210 kg/s and 7 respectively was considered and design specifications of its fan module were determined.

The design of fan module was conducted by the following steps.

- Flow pattern was examined mainly with a conventional quasi-three dimensional streamline-curvature method.
- In order to take into account the effects of the presence of the splitter which separate the fan inlet flow into the bypass flow passing the fan outer bypass passage and the core flow passing the fan inner core booster passage and to design appropriate radial position and shape of the splitter, quasi-three dimensional CFD analysis was also conducted in the latter half of the flow pattern design.
- According to the results of these steps, geometry of each blade row was designed. The shape of blade rows were initially determined by conventional incidence and deviation rules and then iteratively modified by referring the results of 3D CFD analysis until satisfactory performance were achieved.
- Same procedure was used for the design of tandem cascade rotor blade except that the effects of the relative position on aerodynamic performance were also examined to fix the geometry by referring analysis results and preceding basic tandem cascade rotor rig test results.
- And, finally, overall performance was confirmed and fixed by CFD analysis of entire fan module.

## EXPERIMENTAL APPARATUS AND TESTS

### Hardware

The full scale rotational test rig of the booster stage with cropped fan bypass flow outer passage was manufactured for


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aerodynamic performance measurement. The cropping of fan bypass outer passage was selected for obtaining the full scale booster performance under the mass flow and driving power restriction of the test facility. The schematic view of the location of the cropping is shown as dotted line in Fig. 1. The location of the cropping was determined by tracing radial location of constant mass flow determined from the flow capacity of the test facility, from the innermost hub passage of the designed fan module.

By this cropping, bypass ratio of the test rig resulted in around 0.94 compared with 7 of the full fan module.

The sectional view of the rotational test rig is shown in Fig. 2.

As shown in Fig. 2, the test rig is composed of cropped fan rotor in front of the booster stage, cropped fan outlet guide vane in outer bypass passage and booster stage of inlet guide vane, tandem cascade rotor and outlet stator vane in inner core passage.

The rotor assembly of the test rig is also shown in Fig.3.

The tandem cascade rotor of the booster stage is composed of two blisks(bladed disks) as shown in Fig. 4. These two blisks are bolt jointed and the gap between front and rear blades of the tandem cascade is adjusted by setting appropriate relative circumferential position between the two blisks.

**Test Facility**

The booster rotating test rig was installed on the open-loop compressor test stand equipped with 4,000 kW electric motor for driving the rotor. The air entered in the test rig is split into two flow, the bypass flow passing the outer bypass passage and the core flow passing the inner booster passage. The exhaust air from the two passages are guided to atmosphere through two distinct duct and the mass flow is individually controlled by the flow control valves in the two exhaust ducts located downstream of the test rig. The total mass flow and bypass ratio were controlled by these two valves.

**Measurement**

In order to evaluate the overall performance of the booster stage, total pressure and total temperature were measured with 7-head rake probes at the inlet and outlet of the fan rotor blade and with 5-head rake probes at the outlet of the booster outlet stator vane.

And, for obtaining detailed radial flow distributions, traverse measurements were also conducted at the outlet of the fan rotor blade, tandem rotor blade and booster outlet stator vane, respectively. The 3-hole pressure probes were used to measure the total pressure together with the yaw angles. The total temperature were measured with single hole temperature probes aligned with the yaw angles obtained by the 3-hole pressure probes at the same radial positions.

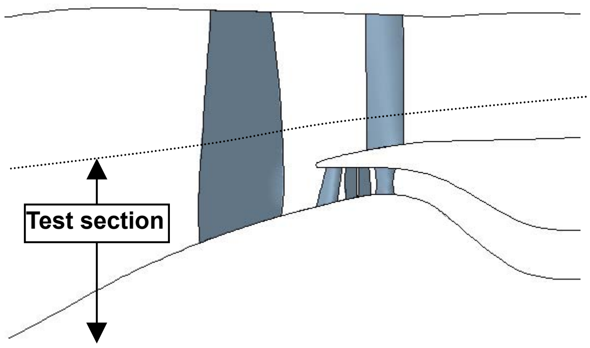


Fig.1 Schematic view of the selected test section

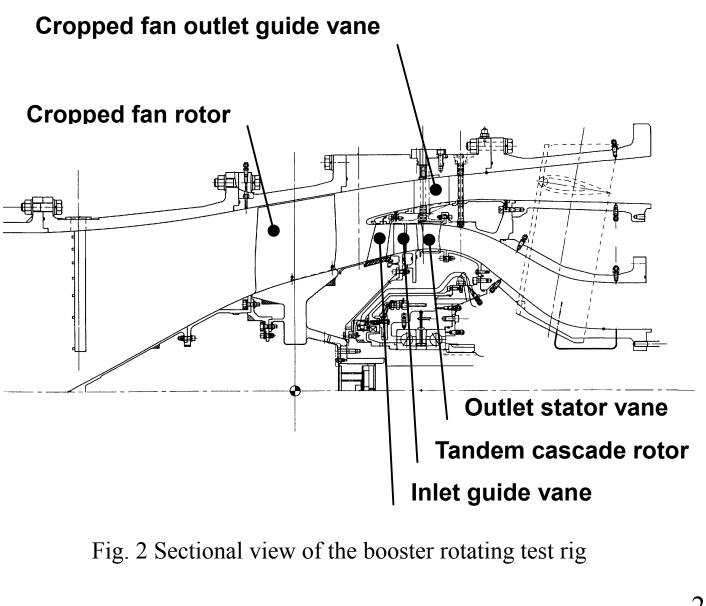


Fig. 2 Sectional view of the booster rotating test rig

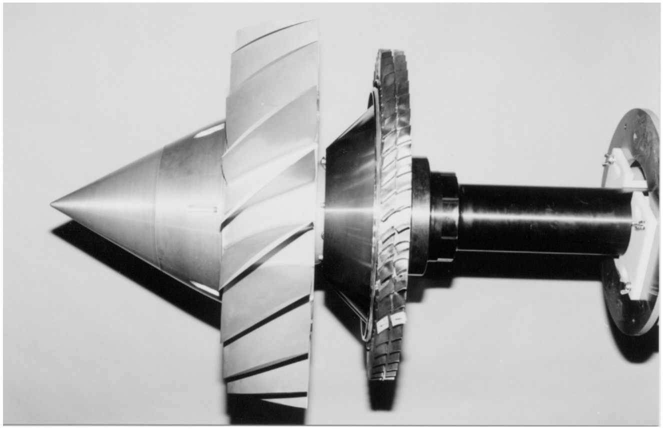

Fig.3 Assembly of cropped fan rotor and booster stage tandem cascade rotor

Fig. 4 Tandem cascade rotor

**Test Method**

The test rig was driven by the electric motor, and the aerodynamic performance was measured at the several mass flow points and rotational speeds. The mass flow was controlled as follows.

- At first, the bypass ratio(the mass flow ratio of the bypass flow and the core flow) was set to the design value at the design rotational speed by adequately setting the two flow control valves downstream of the test rig.
- After that, the amount of the core flow was varied, with the core flow control valve, from choke side to surge side while keeping the constant throttle valve opening for the bypass flow control valve.

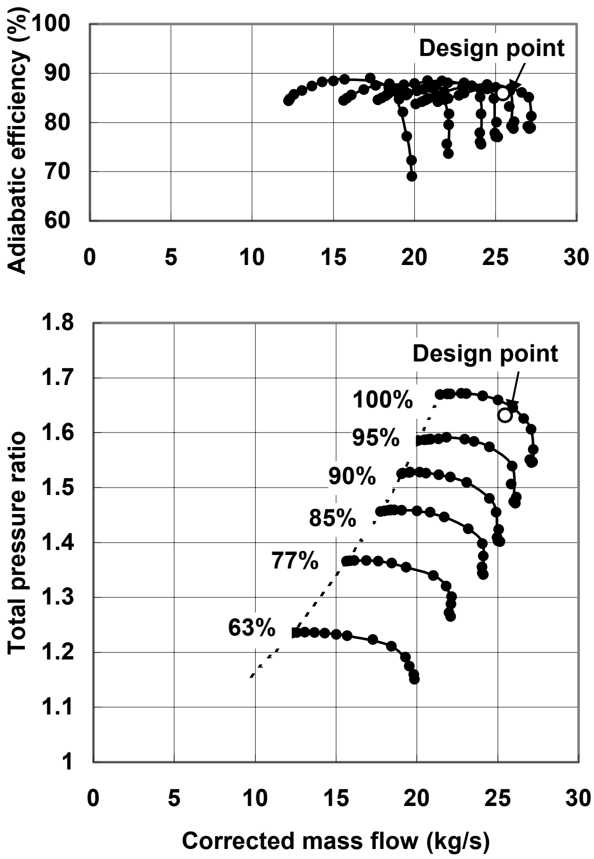


Fig. 5 Fan core and booster stage overall performance map

## TEST RESULTS AND DISCUSSION

**Overall performance**

Fig. 5 shows the overall performance characteristics of the fan core and the booster stage calculated from total pressure and total temperature measured at the fan inlet and the booster stage outlet.

This represents the performance of the booster stage installed in the fan module, namely, combined performance of the fan rotor core portion plus the booster stage(inlet guide vane, tandem cascade rotor and outlet stator vane).

In the figure, test results are shown with black circle symbols and design values are also shown with white circle symbols. The dotted line represents surge limit deduced from the test results.

From this figure, it is noted that the test results at the design speed are slightly higher but well close to the design values in both total pressure ratio and adiabatic efficiency and that the sufficient amount of the surge margin is attained. This would benefit the performance of the engine at off-design conditions by reducing or eliminating the amount of bleed necessary for matching LP and HP spool compressor characteristics.

Table 1 summarizes the experimental results at the rated point compared with the design values. The rated point was determined, on the measured characteristic curve of the total pressure ratio at the design rotational speed, as the point of intersection with the curve of the constant core flow throttle valve opening passing the design point.

In Table 1, total pressure ratio and adiabatic efficiency of the booster stage are separately listed together with the overall values including the fan core portion performance. The surge margin was calculated on the overall performance map(Fig. 5) from the ratio of total pressure ratio and mass flow between the surge point and the rated point at the design rotational speed.

Both pressure ratio and adiabatic efficiency of the booster stage indicate the similar tendency with the overall performance shown in Fig.5 that they well agree with the design values with slightly larger mass flow characteristics and showed the basic capability of the booster stage with tandem cascade rotor.

At the rated point, corrected inlet tip speed of the tandem cascade rotor is 209 m/s and corresponding stage loading factor reaches about 0.48. Here, the stage loading factor is defined as stage adiabatic work divided by the square of the rotor inlet tip speed. This level of loading almost doubles that of the booster stages with conventional rotor and it means that the single tandem booster stage would be able to replace the two stages of the conventional rotor booster.

These results shows the basic capability of the booster stage with tandem cascade rotor.

Table 1 Summary of experimental results

| | | Design | Experiment |
|---|---|---|---|
| Corrected speed (rpm) | | 6176 | 6176 |
| Corrected mass flow (kg/s) | | 25.5 | 25.8 |
| Total pressure ratio ( - ) | Overall* | 1.63 | 1.65 |
| | Fan core** | 1.28 | 1.29 |
| | Booster*** | 1.28 | 1.28 |
| Adiabatic efficiency ( % ) | Overall* | 86 | 87 |
| | Fan core** | 93 | 92 |
| | Booster*** | 81 | 83 |
| Surge margin ( % ) | | >15 | 21.6 |
| NOTES: * Fan inlet to booster stage exit<br>** Fan inlet to booster stage inlet<br>*** Booster stage(Inlet guide vane inlet to outlet stator vane outlet) | | | |

**Radial flow distributions**

In order to examine detailed radial flow distributions, traverse measurements of total pressure, total temperature and absolute flow angle were conducted at the design speed and mass flow of 25.9 kg/s. The measured radial flow distributions together with design distributions at the fan rotor outlet, the tandem cascade rotor outlet and the exit stator vane outlet are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. In these figures, total pressure and total temperature are represented as the ratio against the fan inlet conditions.

In general, the pattern of measured radial flow distributions are close to the design distributions, qualitatively.

The discrepancies of the measured flow angles and the design flow angles are obvious at the tip region of tandem cascade rotor and outlet stator vane as shown in Fig.7 and Fig. 8. They are due to the existence of the tip clearance of the tandem cascade rotor and, to some extent, inevitable phenomena but is not well predicted in the design phase. Same consideration is applicable to the total pressure of the tandem cascade rotor tip region.

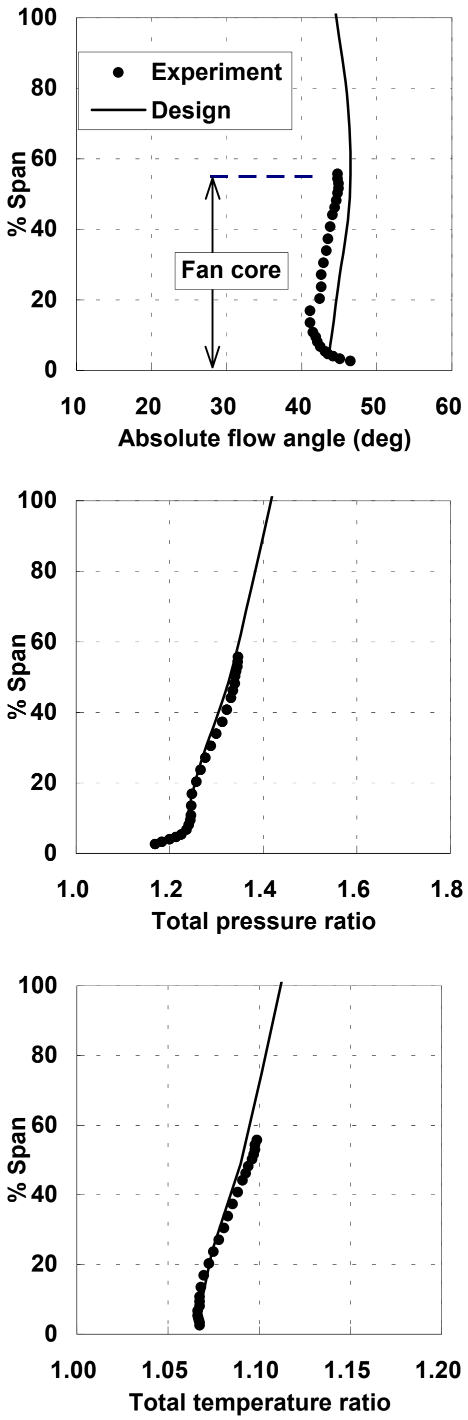


Fig.6 Radial distributions of absolute flow angle, total pressure ratio and total temperature ratio at fan rotor outlet(booster stage inlet) (Corrected speed: 100%, Corrected mass flow 25.9 kg/s)

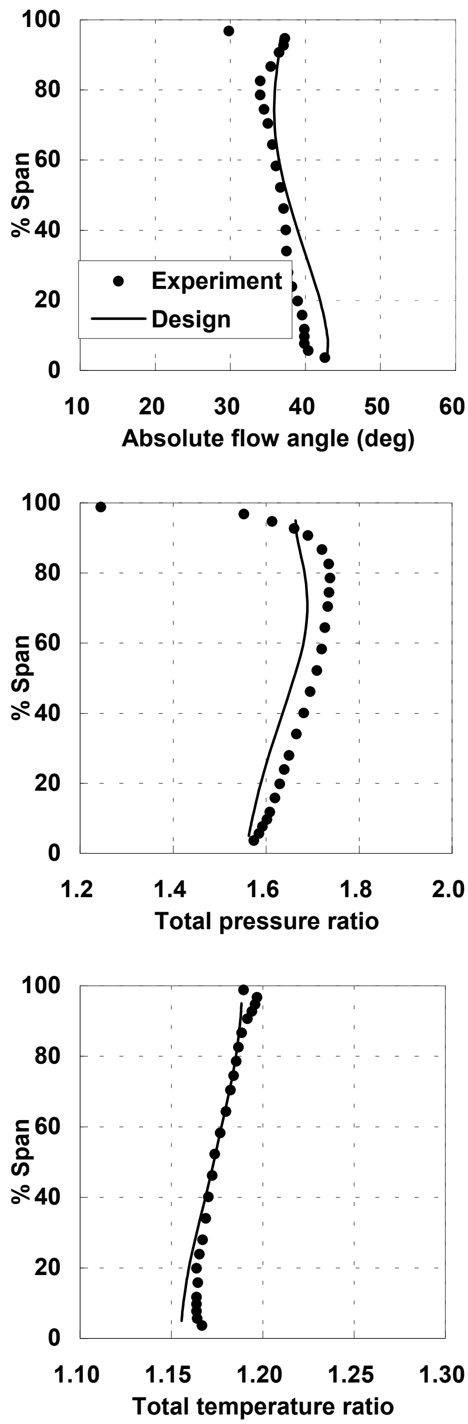


Fig.7 Radial distributions of absolute flow angle, total pressure ratio and total temperature ratio at tandem cascade rotor outlet (Corrected speed: 100%, Corrected mass flow: 25.9 kg/s)

Concerning the total pressure distributions, measured distribution is close to the design distribution at the outlet stator vane outlet while the measured distribution is higher than the design at the tandem cascade rotor outlet. This may indicate the deficiency of the outlet stator vane.

So, there exits a room and possibility for further improvement of the performance beyond the results obtained by this study.

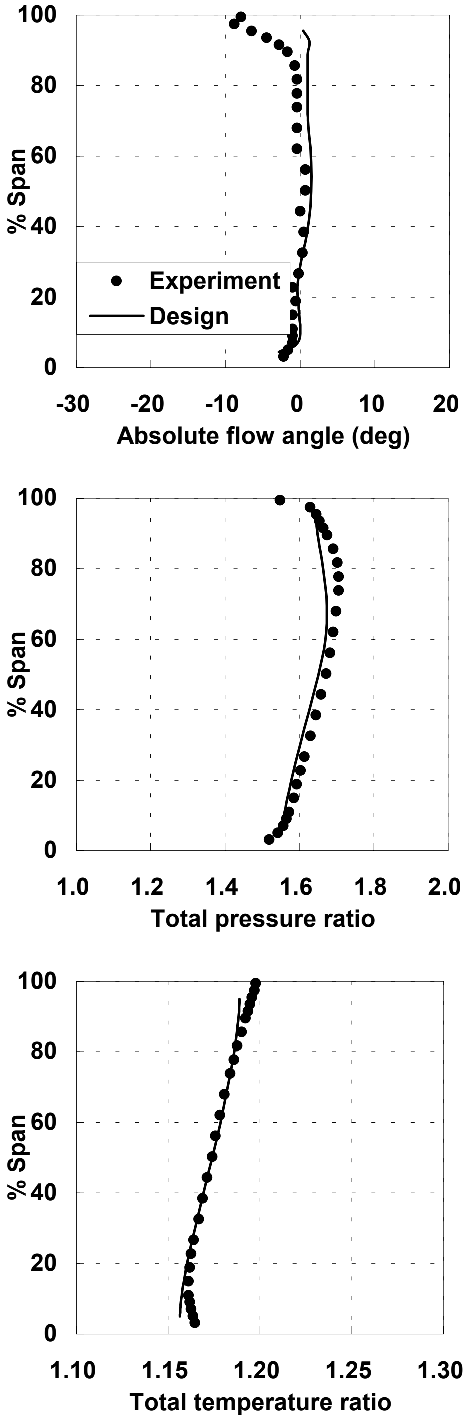


Fig.8 Radial distributions of absolute flow angle, total pressure ratio and total temperature ratio at outlet stator vane outlet(booster stage outlet) (Corrected speed: 100%, Corrected mass flow: 25.9 kg/s)

## CONCLUSIONS

A booster stage with tandem cascade rotor blade was designed and tested to evaluate the basic performance and its applicability to high bypass ratio fan engines as a replacement for conventional multi-stage boosters.

Test results revealed the basic characteristics of a booster stage with tandem cascade rotor blade. Measured overall performance of pressure ratio and efficiency of the booster test rig was nearly match the design and showed the possibility of applying the tandem cascade rotor to the booster stage.

Furthermore, sufficient amount of the surge margin was attained and this would benefit the off-design performance of the engine by reducing or eliminating the amount of the bleed necessary for matching LP and HP spool compressor characteristics.

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