

Numerical analysis for the matching of the core driven compression system in a double bypass engine

ZHANG Xin, LIU Bao-jie

(National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics,
School of Jet Propulsion, Beijing University of Aeronautics and Astronautics,
Beijing 100191, China)

Abstract: The numerical analysis for the matching of the core driven compression system in a double bypass variable cycle engine was presented in this paper. The system consists of a one-stage-core driven fan stage (CDFS), an inner bypass duct and a five-stage high pressure compressor (HPC), providing two basic operating modes: the single bypass mode and the double bypass mode. Variable vanes are necessary to realize the mode switch of the system. The correct matching in the double bypass mode requires a proper combination of the mass flow, total pressure ratio and blade speed. The work capacity of the system decreases in the double bypass mode and the pressure ratio tends to decrease more for the CDFS and the front stages of the HPC. The overall system efficiency is higher in the double bypass mode. The radial distributions of aerodynamic parameters are similar in different modes. The notable redistribution of mass flow downstream the CDFS in the single bypass mode leads to strong radial flows and additional mixing losses. The absolute flow angles into the inner bypass increase for the inner span and decrease for the outer span when the system is switched from the single bypass mode to the double bypass mode.

Key words: numerical analysis; aerodynamic; double bypass variable cycle engine;
core driven compression system; core driven fan stage; operating mode

CLC number: V231.3

Document code: A

Nomenclature

Δh_t	Stagnation enthalpy rise	m	Mass flow rate
U_{mid}	Midspan blade speed	p	Static pressure
$U_{\text{mid,cor}}$	Corrected midspan blade speed	R	Gas constant
$V_{x,\text{avg}}$	Average axial velocity	T	Static temperature
ψ	Loading coefficient($\psi = \Delta h_t / U_{\text{mid,cor}}^2$)	Ma	Mach number
ϕ	Flow coefficient($\phi = V_{x,\text{avg}} / U_{\text{mid}}$)	κ	Ratio of specific heat capacities
α	Absolute flow angle	p_0	Standard stagnation pressure
β	Relative flow angle	T_0	Standard stagnation temperature
A	Cross-section area	η_p	Polytropic efficiency
ρ	Density	π	Total pressure ratio

Subscript

t	stagnation properties	db	double bypass mode
sb	single bypass mode		

Received: 2010-11-15; **revision received:** 2011-03-17

E-mail: zhangxin@sjp.buaa.edu.cn

Introduction

The benefits of a variable cycle engine (VCE) have been identified in early researches, including tuning the cycle features, e. g. the bypass ratio and pressure ratio, to the unique mission requirements to provide more efficient operation in different operating conditions than fixed-cycled engines, reducing the engine noise and exhaust emissions^[1-4]. Many VCE concepts have been investigated since 1960s, in which the concept of the double bypass VCE with the core driven fan stage (CDFS) proposed by General Electric has been identified as a leading candidate for advanced supersonic cruise aircrafts^[5-8].

The double bypass VCE has two basic operating modes: the single bypass mode for supersonic cruise and acceleration; the double bypass mode for subsonic cruise and take off^[9]. The fan in a double bypass VCE is split into two “blocks”: front and rear. The rear block is driven by the high pressure turbine, as opposed to the conventional low pressure turbine drive arrangement for all existing turbofan engines, therefore it is called the core driven fan stage, which is a key component of the double bypass VCE. The concept of the CDFS is a logical benefit for variable cycle propulsion system; in fact, it has broad applicability to any low pressure ratio, mixed mission requirement including single bypass (only) engine arrangements. The unique technical payoffs of the core driven concepts are summarized in Ref. [10].

The structure of the remainder of the paper is as follows. The aerodynamic description of the core driven compression system is summarized briefly first, followed by the analysis for the overall stage aerodynamic parameters. Then the radial distributions of aerodynamic parameters are discussed for all the blade rows. Flow characteristics among the CDFS, the high pressure compressor (HPC) and the inner bypass duct are also analyzed. Lastly, main conclusions of the matching characteristics of the core driven compression system are enumerated.

1 Aerodynamic description of the core driven compression system

The core driven compression system consists of a one-stage CDFS, an inner bypass duct and a five-stage HPC, as shown in Fig. 1. The CDFS has a variable inlet guide vane (IGV) and a variable stator. The HPC, of which the first two stages have variable geometry vanes, has no IGV. There is a variable outlet guide vane (OGV) in the inner bypass duct. In fact, there are different configurations for the core driven compression system, and the benefits of the present configuration are summarized in Ref. [11].

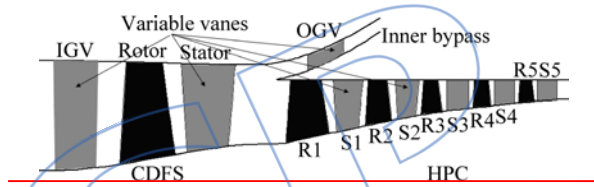


Fig. 1 Sketch of the core driven compression system

1.1 Aerodynamic description of the CDFS

The aerodynamic parameters of the CDFS are presented in Table 1. All the normalized parameters in Table 1 and Table 2 are normalized by the corresponding CDFS design values in the single bypass mode. In contrast to a conventional fan, the CDFS has two basic operating modes: the design pressure ratio was $1.51 : 1$ with an isentropic efficiency goal of 87.4% in the single bypass mode; the desire goal was a pressure ratio of $1.25 : 1$ with an isentropic efficiency of 86.9% in the double bypass mode. The inlet corrected mass flow was reduced by 20% in the double bypass mode. The loading coefficient is defined by $\Delta h_t / U_{mid,cor}^2$; the flow coefficient is defined by $V_{x,avg} / U_{mid}$.

The CDFS tip speeds are excessive high for the design pressure ratios, leading to consequent low loading coefficients in both modes (Table 1). This is because the HPC tip speeds are proportional to the CDFS tip speeds, hence high CDFS tip speeds are required to ensure adequate HPC tip speeds, avoiding burdensome loading

Table 1 CDFS aerodynamic parameters

Aerodynamic parameters	Operating mode	
	Single bypass mode	Double bypass mode
Total pressure ratio	1.50	1.25
Isentropic efficiency/%	87.4	86.9
Stall margin/%	18	20
Corrected tip speed/(m/s)	430	397
Dimensionless corrected mass flow/%	100	80
Loading coefficient	0.36	0.22
Flow coefficient	0.46	0.40
IGV variation	Open	23 degrees closed
Inlet radius ratio		0.56
Outlet radius ratio		0.67

levels for the HPC. Nevertheless, high tip speeds mean high Mach numbers into the CDFS rotor, resulting in high losses associated with shocks and viscous shear. A pre-swirl-producing IGV was then introduced to reduce the inlet Mach number in the single bypass mode, and it was closed 23 degrees to provide the mass flow reduction in the double bypass mode.

The flow coefficient varies from 0.46 to 0.41 when the CDFS is switched from the single bypass mode to the double bypass mode, causing the stator inlet flow angles to rise from 43 degrees to 46 degrees^[11-12]. This leads to either a reduction in stall margin in the double bypass mode or a decrease in efficiency in the single bypass mode. An outlet-adjustable-variable curva-

ture CDFS stator was employed to settle the problem. The CDFS stator was used to modulate the HPC mass flow in different operating modes, of which the feasibility had been validated in Ref. [9]: it produced a 15 degrees pre-swirl for the HPC in the single bypass mode, and the overall flow turning was 28 degrees; when the system was switched to the double bypass mode, its outlet was closed 10 degrees to provide the desire mass flow for the HPC (Table 2) and the overall flow turning was therefore less than that in the single bypass mode despite the incidence increase. Although the CDFS stator was set away from the design condition in the double bypass mode, the overall flow turning decreased, still providing favorable performance.

Table 2 HPC aerodynamic parameters

Design objectives	Operating mode	
	Single bypass mode	Double bypass mode
Total pressure ratio	5.92	4.6
Isentropic efficiency/%	87.5	87.5
Stall margin/%	17	20
Dimensionless corrected mass flow/%	61.3	50.3
Inner bypass ratio	0.16	0.30
Corrected tip speed/(m/s)	370	354
CDFS stator variation	Open	10 degrees closed
Inlet radius ratio		0.72
Outlet radius ratio		0.92

1.2 Aerodynamic description of the high pressure compressor

The HPC aerodynamic parameters and the inner bypass ratio, which is defined by the ratio of the inner bypass mass flow to the HPC mass flow, are shown in Table 2. The HPC also has two operating modes: the design goal was a pressure ratio of 5.92 : 1 with an isentropic efficiency of 87.5% in the single bypass mode and a pressure ratio of 4.6 : 1 with an isentropic efficiency of 87.5% in the double bypass mode. The inner bypass ratios were 0.16 and 0.30 in the single bypass mode and double bypass mode respectively.

2 Analysis for the matching of the core driven compression system

All the compressors are designed with a particular condition in mind, usually referred to as the design point or matching point. The design point is normally chosen where the compressor will operate for much of the time or where its performance is particularly critical, generally near the maximum speed and pressure rise that the machine can deliver. However, the core driven compression system is supposed to operate in two basic modes. Once the system is designed based on the single bypass mode, the general layouts are fixed. Then it is the correct matching of the stages which is most critical in deciding if the system could meet the desire performance in the double bypass mode. When the core driven compression system is switched from the single bypass mode to the double bypass mode: the CDFS IGV is closed 23 degrees to deliver the desire mass flow and pressure ratio; meanwhile, the CDFS stator and the first two stators of the HPC are closed 10, 9, 3 degrees respectively to adjust the HPC in the double bypass mode.

2.1 Analysis for the stage parameters

A feature of the system operation in the double bypass mode is that the work per stage is much different from that in the single bypass

mode. Fig. 2 illustrates the pressure ratio and efficiency of each stage: when the system operates in the double bypass mode, the pressure ratio decreases more for the CDFS and the front stages of the HPC. The CDFS pressure ratio falls from 1.50 to 1.23 and the pressure ratio of the HPC first stage decreases from 1.60 to 1.46, however, the pressure ratio of the HPC last stage varies only from 1.30 to 1.26, implying relative highly loaded rear stages for the HPC. The overall pressure ratio of the system is 8.94 in the single bypass mode and 5.74 in the double bypass mode.

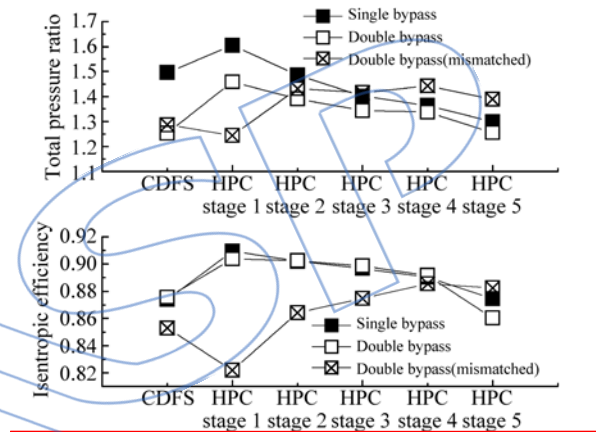


Fig. 2 Total pressure ratio and isentropic efficiency of each stage in the single and double bypass mode

Fig. 3 shows the loading coefficients and the flow coefficients of each stage at the design condition in both modes. The loading coefficient distribution in the double bypass mode is analogous to that in the single bypass mode despite the variation in the pressure ratio distribution. The flow coefficient decreases for the CDFS and the front stages of the HPC, and slightly increases for the HPC rear stages. A dimensionless group ϕ_{db}/ϕ_{sb} is employed to understand the different distribution of flow coefficients in different modes. In the relation $\phi = V_{x,avg}/U_{mid}$, the average axial velocity is $V_{x,avg} = \dot{m}/\rho A$ and the density is given by $\rho = p/RT$. For a given flow rate, the static and stagnation variables are related by functions only of flow Mach number. The ϕ_{db}/ϕ_{sb} can be written as

$$\frac{\phi_{db}}{\phi_{sb}} = \frac{m_{db}}{m_{sb}} \cdot \frac{U_{mid,db}}{U_{mid,sb}} \cdot \frac{p_{t,db}}{p_{t,sb}} \cdot \frac{T_{t,db}}{T_{t,sb}} \cdot \frac{f(Ma_{sb})}{f(Ma_{db})} \quad (1)$$

$f(Ma) = \left[1 + \frac{\kappa-1}{2} Ma^2\right]^{-\frac{1}{\kappa-1}}$ is a function of

Mach number in Eq. (1). The ratio $\frac{f(Ma_{sb})}{f(Ma_{db})}$ can

be considered as unit compared with the other terms at the right side of Eq. (1). For the given mass flow and blade speed in different modes,

ϕ_{db}/ϕ_{sb} is proportional to $\frac{p_{t,sb}/T_{t,sb}}{p_{t,db}/T_{t,db}}$. It is useful

to express this in terms of the total pressure ratio and total temperature ratio, so

$$\frac{p_{t,sb}/T_{t,sb}}{p_{t,db}/T_{t,db}} = \frac{(p_{t,sb}/p_0)/(T_{t,sb}/T_0)}{(p_{t,db}/p_0)/(T_{t,db}/T_0)} \quad (2)$$

p_0 and T_0 are the standard stagnation pressure and temperature respectively. The total temperature ratio can be expressed by the total pressure ratio to the power $(\kappa-1)/\kappa\eta_p$, with η_p being the polytropic efficiency. The ratio of flow coefficient in the single bypass mode to that in double bypass mode can then be approximate

$$\frac{\phi_{db}}{\phi_{sb}} = \frac{m_{db}}{m_{sb}} \cdot \frac{U_{mid,db}}{U_{mid,sb}} \cdot \frac{\pi_{sb}^{1-(\kappa-1)/\kappa\eta_{p,sb}}}{\pi_{db}^{1-(\kappa-1)/\kappa\eta_{p,db}}} \quad (3)$$

It should be noted that the total pressure ratio in Eq. (3) is the total pressure ratio at the inlet of certain blade row, not the overall pressure ratio of the system. The flow coefficient variation in different modes is then related to the mass flow, blade speed and pressure ratio by Eq. (3). The mass flow reduction tends to decrease the flow coefficient in the double bypass mode and the reduced total pressure ratio compensates this effect, resulting in the flow coefficient distribution in Fig. 3.

Eq. (3) relates variation in flow coefficient to the ratio of mass flow, blade speed and pressure ratio in different modes. Because it is the flow angles into each blade row which really determine whether a stage is operating correctly and the angles depend on the flow coefficient. Then Eq. (3) actually put a limit on the system operation in the double bypass mode. For a given blade speed, there is an optimum combination of mass flow and overall pressure ratio that pro-

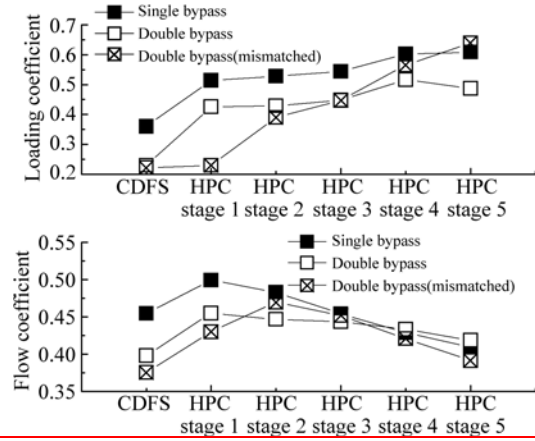


Fig. 3 Loading coefficient and flow coefficient of each stage stages in the single and double bypass mode

vides the best performance in the double bypass mode. Consider the operating condition of the HPC stator 5 in the double bypass mode: the correct operation requires the same flow angles, i. e. same flow coefficient into the stator; given a value of mass flow, the optimal overall pressure ratio can be inferred from Eq. (3); a higher pressure ratio will inevitably lead to a reduction in the flow coefficient and hence an increase in the flow angles into HPC stator 5, raising the aerodynamic loading; this in turn means a reduction in the stall margin of the system in the double bypass mode. The reduction in the mass flow requires the overall pressure ratio to decrease for the correct matching of the system in the double bypass mode.

Furthermore, the blade speed also plays an important role in the matching of the core driven compression system. For a given mass flow, a reduction in the blade speed can decrease the flow angles into the last stator in the double bypass mode, permitting the system to produce the same overall pressure ratio without increasing the loading of HPC stator 5. On the other hand, the blade speed also influences the work per stage and the system efficiency. Consider, for example, an increase in the blade speed with the mass flow and total pressure ratio fixed in the double bypass mode: the mass flow into the HPC tends to rise due to the increased blade speed, then the CDFS stator has to be closed

more to deliver the desire mass flow into the HPC; as a result, the pressure ratio of the HPC first stage decreases, could even be lower than that of the HPC last stage, leading to an immoderate loading distribution along the stages and low efficiency for the system. Numerical results show that the same blade speed in the double bypass mode as that in the single bypass mode would lead to a pressure ratio of only 1.28 for the HPC stage 1 and a reduction of 3% in system efficiency (shown as the mismatched case in Fig. 2 and Fig. 3).

To understand the efficiency variation in Fig. 2, the rotor efficiency and stator total pressure recovery coefficient of each stage are illustrated in Fig. 4. The CDFS efficiency is lower in the double bypass mode than that in the single bypass mode, although the rotor efficiency is higher and the stator loss is smaller. This is because CDFS pressure ratio is much lower in the double bypass mode, and small losses in the stator would bring considerable reduction in the stage efficiency. The increase in stator loss for the first stage of the HPC is mainly caused by the negative incidence in the double bypass mode. Because the stator is closed 9 degrees and flow direction into it only increase by about 3.5 degrees. The decreased rotor pressure ratio and the stator total pressure recovery coefficient result in the efficiency reduction for HPC stage 1 in the double bypass mode. The HPC rotor 5 also operates at negative incidence in the double bypass mode, which can be inferred from the slightly increased flow coefficient in Fig. 3, offering a much lower efficiency than that in the single bypass mode. However, preferable total pressure recovery coefficient is found in stator 5 because of the higher flow coefficient, which means decreased loading in the double bypass mode. The overall efficiency of the system is 86.8% in the single bypass mode and 87.2% in the double bypass mode.

The feature of the stage behavior in the double bypass mode is summarized as follows. The work capacity of the system decreases in the

double bypass mode mainly because of the reduction in the mass flow. The correct matching in the double bypass mode requires a proper combination of mass flow, pressure ratio and blade speed. The pressure ratio decreases more for the CDFS and the HPC front stages in the double bypass mode. The overall efficiency is higher in the double bypass mode because of higher efficiency for most rotors.

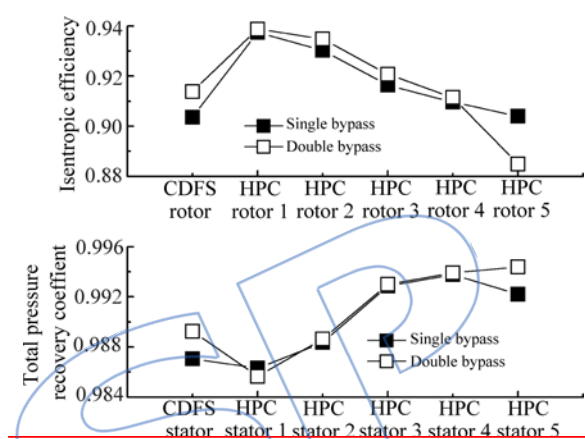


Fig. 4 Rotor isentropic efficiency and stator total pressure recovery coefficient in the single and double bypass mode

2.2 Analysis for the radial distribution of the aerodynamic parameters

The radial distributions of rotor inlet relative flow angles in both modes are illustrated in Fig. 5. The relative flow angles show similar distributions along the span for all the rotors, implying correct matching in general for the system operation in the double bypass mode. The negative incidence into the CDFS rotor, especially near 10% span, indicates somewhat low aerodynamic loading relative to the optimal operating condition. Positive incidences are found for HPC rotor 1 and rotor 2 while negative incidence is found for the rest, indicating that the pressure ratio is a little high for the front stages and low for the rear stages of the HPC in respect of matching of flow angles. Incorporated with the pressure ratio distribution shown in Fig. 2, the correct matching of rotor inlet flow angles require relative high pressure ratio for the HPC rear stages.

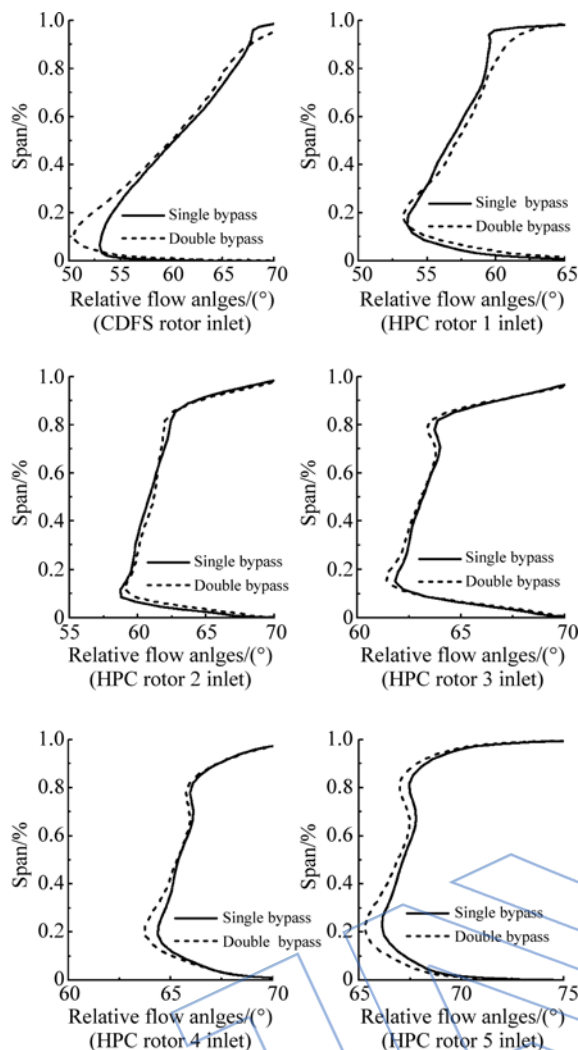


Fig. 5 Radial distributions of rotor inlet relative flow angles in the single and double bypass modes

The radial distributions of rotor inlet relative Mach numbers are shown in Fig. 6. When the system is switched to the double bypass mode, the relative Mach numbers decrease uniformly along the span for all the rotors: the tip relative Mach number reduces from 1.26 to 1.08 for the CDFS rotor; it reduces from 1.12 to 0.97 for HPC rotor 1 and reduces from 0.89 to 0.88 for HPC rotor 5. The extent in Mach number reduction decreases from the front to the rear stages, which is the essential cause for the nonuniform variation in the pressure ratio distribution in different modes shown in Fig. 2. The radial distribution of the rotor total pressure ratio, shown in Fig. 7, related to the distribution of relative flow angles and relative Mach numbers,

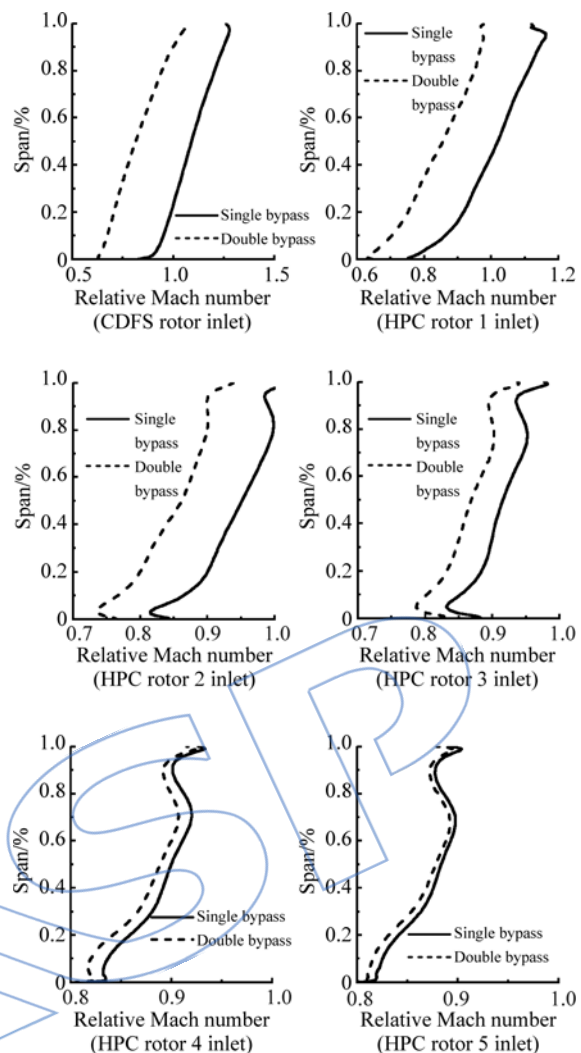


Fig. 6 Radial distributions of rotor inlet relative Mach numbers in the single and double bypass mode

also shows analogical behavior in both modes.

In contrast to the relative flow direction into the rotors, the inlet flow angles for all the stators are much different in the two modes, as shown in Fig. 8. The inlet flow angles increase for the first three stators and decrease for the rest due to the variation in the flow coefficient, which depend on the pressure ratio distribution shown in Fig. 2 and can be understood from Eq. (3). Although the flow angles into the CDFS stator increase by about 4 degrees in the double bypass mode, its outlet is closed 10 degrees (with inlet fixed), providing even less flow deflection. The increase in the inlet flow angles for HPC stator 1 and stator 2 are 3.5 degrees and 1 degrees respectively, meanwhile they are turned

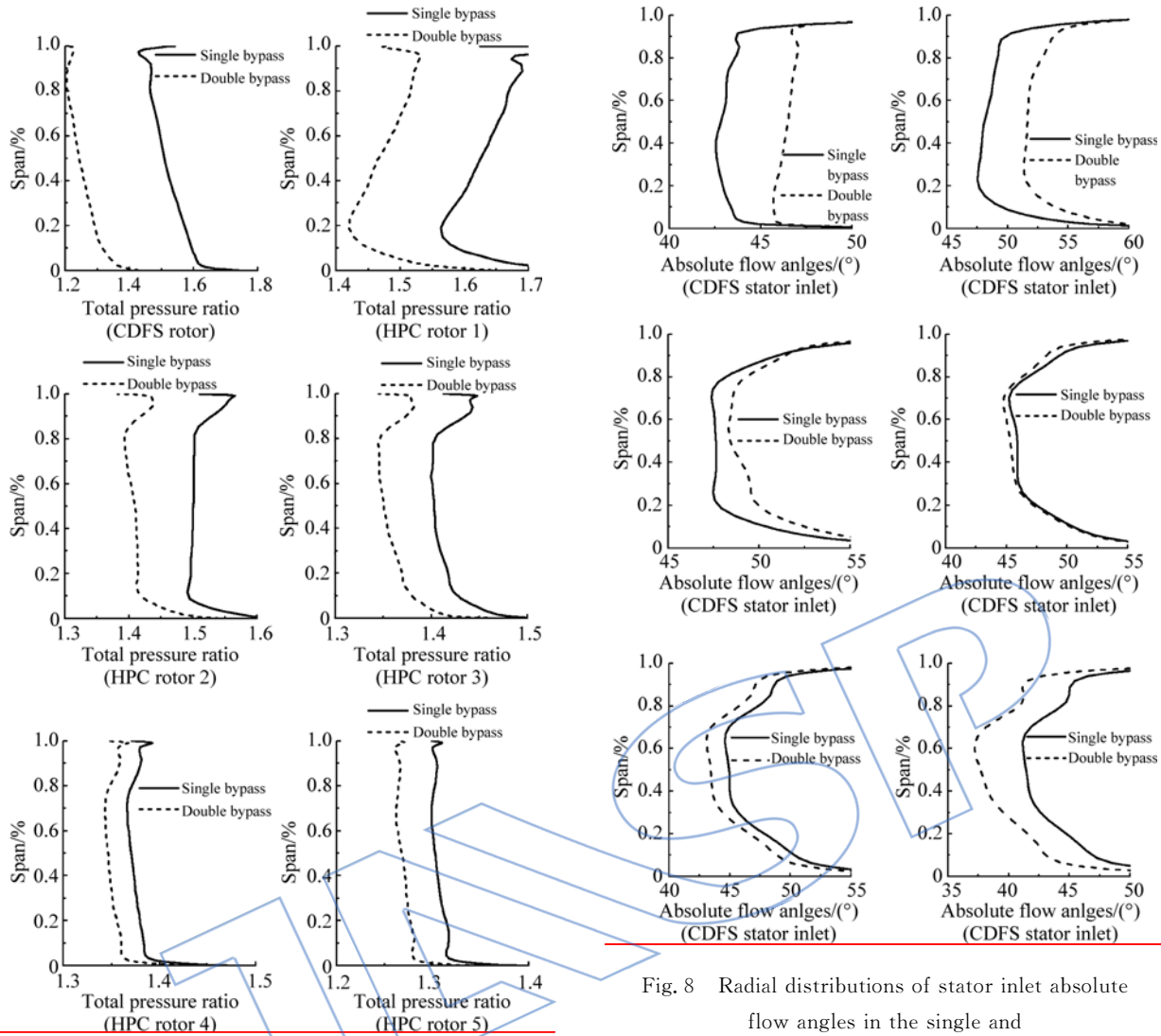


Fig. 7 Radial distributions of rotor total pressure ratio in the single and double bypass mode

by 9 degrees and 3 degrees respectively. The first two stators of the HPC are operating at negative incidence in the double bypass mode.

Fig. 9 illustrates the diffusion factor distributions along the span for the stators. The loading of CDFS stator decreases remarkably due to the reduced flow deflection. Likewise, the rise in the inlet flow angles does not lead to the increased loading for HPC stator 1 and stator 2 because of the changeless overall flow turning. The loading decreases for the last three stators of the HPC, which are of fixed geometry, due to the reduction in the inlet flow angles.

Although the operating mode influences on the operation of the rotors and stators remark-

Fig. 8 Radial distributions of stator inlet absolute flow angles in the single and double bypass modes

ably, the radial distributions of the aerodynamic parameters are similar in different modes. The inlet relative Mach numbers and pressure ratio descend more for the front stages in the double bypass mode. The correct matching of rotors requires relative low pressure ratio for the HPC front stages and high pressure ratio for the HPC rear stages. The flow angles into the stators increase for the first three stators and decrease for the rest in the double bypass mode, however, the increased flow angles do not raise loading for the stators due to the variable geometry.

2.3 Analysis for flow characteristics between the CDFS and the HPC (and the inner bypass)

The inner bypass ratio increases from 0.16 to 0.30 when the system is switched from the single bypass mode to the double bypass mode,

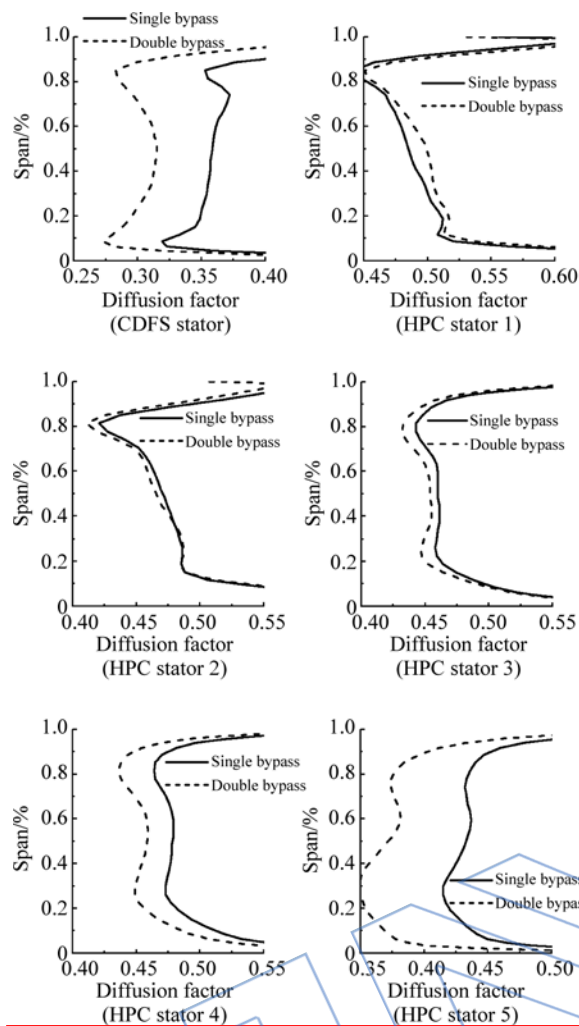


Fig. 9 Radial distributions of stator diffusion factor in the single and double bypass modes

indicating the mass flow distribution downstream the CDFS varies remarkably in different modes. Fig. 10 shows the comparison of the dimensionless axial velocity at the CDFS outlet with that at the HPC and inner bypass inlet. The position of CDFS outlet, HPC and inner bypass inlet are illustrated in Fig. 11. The axial velocity at the CDFS outlet is lower in the double bypass mode due to the reduced total mass flow. The radial distribution is more uniform in the double bypass mode, indicating that the CDFS operation tends to provide a higher inner bypass ratio in the double bypass mode than that in the single bypass mode. In the single bypass mode, the dimensionless axial velocity into the HPC is higher than that at the CDFS outlet, and the axial velocity is lower at the inner bypass inlet, implying a notable redistribution of mass flow

downstream the CDFS. The operation of CDFS in the single bypass mode provides an inner bypass ratio higher than 0.16, and then a relative high inner bypass back pressure is needed to push some mass flow into the HPC. This in turn means a notable inward radial flow at the leading edge of the splitter (Fig. 12), which may cause a local high incidence. The considerable radial inward flow leads to an entropy increase downstream of the CDFS (Fig. 13) indicating increased mixing losses. The increased entropy near the hub from the CDFS outlet to the HPC inlet in both modes probably comes from the thickened boundary layer, which can be inferred from the axial velocity defect near the hub (Fig. 10).

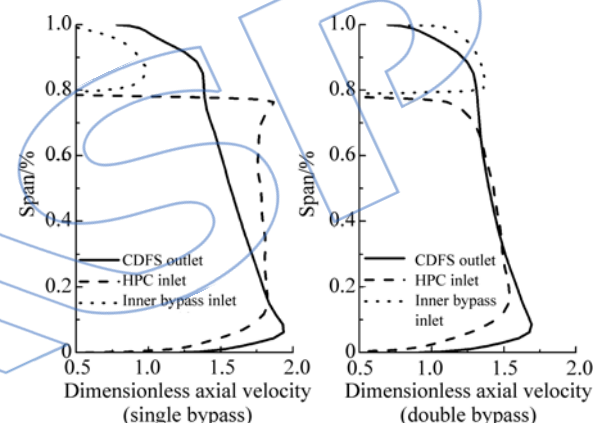


Fig. 10 Comparison of the dimensionless axial velocity at CDFS outlet with that at the HPC and inner bypass inlet

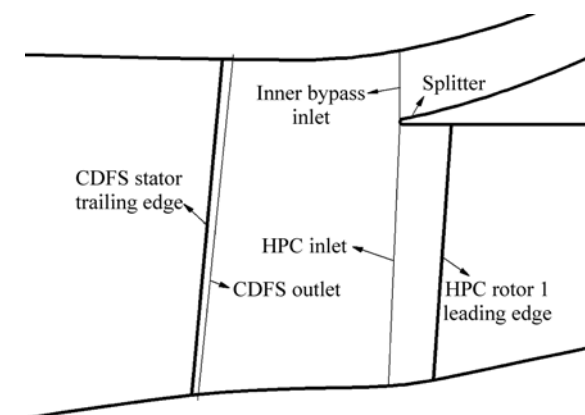


Fig. 11 Sketch of CDFS outlet and HPC/inner bypass inlet

When the system operates in the double bypass mode, the CDFS operation provides an in-

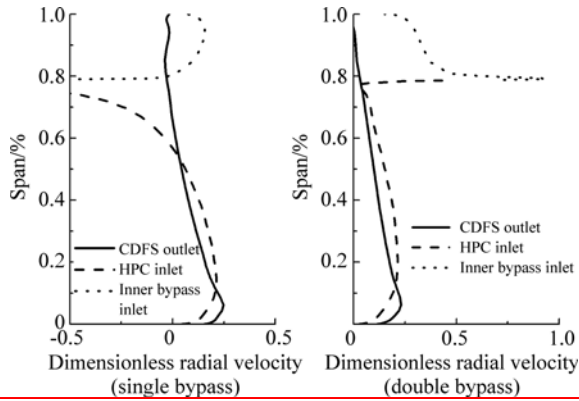


Fig. 12 Comparison of the dimensionless radial velocity at the CDFS outlet with that at HPC and inner bypass inlet

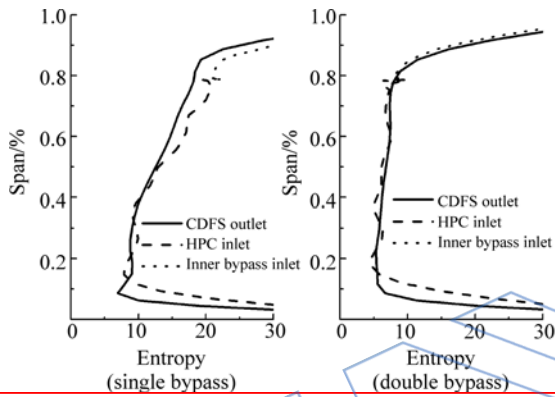


Fig. 13 Comparison of the entropy at the CDFS outlet with that at the inlet of the HPC and inner bypass

ner bypass ratio close to the desire value, which can be inferred from the axial velocity radial distribution in the double bypass mode (Fig. 10). Only a small proportion of mass flow is pushed into the inner bypass, resulting in much weaker radial outward flow at the HPC inlet. Noted that the strong radial outward flow in at the inner bypass inlet that can be also observed in the single bypass mode (Fig. 12), comes partly from the outward flowpath of the inner bypass (Fig. 11) and leads to negligible additional losses downstream the CDFS (Fig. 13).

The redistribution of axial velocity downstream the CDFS causes a redistribution of absolute flow angles, i. e. the absolute flow angles into the HPC and inner bypass are not exactly that produced by the CDFS stator, as illustrated in Fig. 14. The increased flow angles near the

hub are because of the axial velocity defect downstream the CDFS in both modes. The increased flow angles near the HPC tip in the single bypass mode is due to the locally increased axial velocity. The redistributed flow angles at the HPC inlet will not cause considerable matching problems, which can be inferred from the relative flow angles into HPC rotor 1 shown in Fig. 5. However, the radial distribution of the flow angles into the inner bypass shows notable variation in different modes, as illustrated in Fig. 14: when the system is switched from the single bypass mode to the double bypass mode, the inlet flow angles increase for the inner span and decrease for the outer span. Then problem rises in the design of the inner bypass OGV: it would never operate at its optimum due to the variation in radial distribution of inlet flow angles. The flow angles into the OGV in the double bypass mode increases by about 4 degrees at 10% span and decreases by about 4 degrees at 90% span compared with that in the single bypass mode.

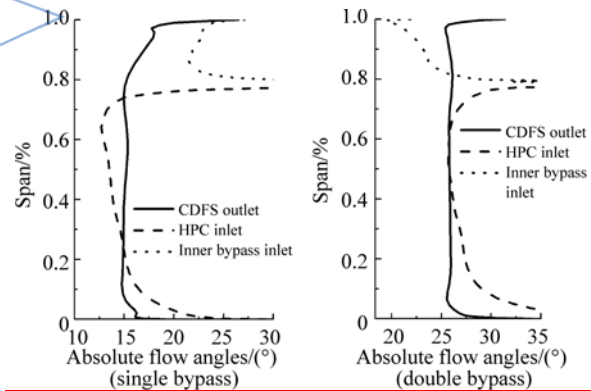


Fig. 14 Comparison of the absolute flow angles at the CDFS outlet with that at the inlet of the HPC and inner bypass

To be summarized, the CDFS operation in the single bypass mode does not provide the desire mass flow distribution and hence cause a strong radial inward flow near the splitter, resulting in additional mixing losses downstream the CDFS. In the double bypass mode, the CDFS provides a more desired mass flow distribution for the HPC and the inner bypass; then

the radial flow is much weaker and the related entropy rise is less than that in the single bypass mode. The absolute flow angles into the inner bypass increase for the inner span and decrease for the outer span, which is related to the different axial velocity radial distributions into the inner bypass.

3 Conclusions

The matching of the core driven compression system in a double bypass engine is analyzed and the main conclusions are summarized as follows:

Variable geometry vanes are necessary to realize the mode switch for the system and the correct matching of the system in the double bypass mode requires a proper combination of mass flow, overall pressure ratio and blade speed. The pressure rise capacity of the system decreases abruptly in the double bypass mode due to the considerable reduction in the HPC mass flow in this condition. The overall efficiency is higher in the double bypass mode because of the improved efficiency for most rotors.

The radial distributions of the aerodynamic parameters show similar behavior in different modes. The correct matching of rotors requires relative low pressure ratio for the CDFS and HPC front stages, and high pressure ratio for the HPC rear stages. The inlet relative Mach numbers and pressure ratio descend more for the front stages in the double bypass mode.

Strong radial flows are found at the HPC inlet in the single bypass mode due to the redistribution of mass flow, leading to additional mixing losses downstream the CDFS and they

are much weaker in the double bypass mode. The absolute flow angles into the inner bypass increase for the inner span and decrease for the outer span when the system is switched from the single bypass mode to the double bypass mode.

References:

- [1] Mclean F E. Supersonic cruise technology[R]. NASA SP-472, 1985.
- [2] Uillis E. Variable cycle engines for supersonic cruise aircraft[R]. NASA TMX-73463, 1976.
- [3] Maclin H, Krause F. Propulsion technology for future commercial aircraft[R]. AIAA Paper 2003-2544, 2003.
- [4] Koff S G, Koff B L. Engine design and challenges for the high mach transport[R]. AIAA Paper 2007-5334, 2007.
- [5] Messersmith N. Future high Mach propulsion[R]. AIAA Paper 2003-2613, 2003.
- [6] Fishbach L H, Stitt L E, Stone J R, et al. NASA Research in supersonic propulsion: a decade of progress[R]. AIAA Paper 1982-1048, 1982.
- [7] Allan R D. General Electric Company variable cycle engine technology demonstrator program[R]. AIAA Paper 1979-1311, 1979.
- [8] Brown R. Integration of a variable cycle engine concept in a supersonic cruise aircraft [R]. AIAA Paper 1978-1049, 1978.
- [9] French M W, Allen G L. NASA VCE test bed engine aerodynamic performance characteristics and results [R]. AIAA Paper 1981-1594, 1981.
- [10] Vdoviak J W, Ebacher J A. VCE test bed engine for supersonic cruise research[C]//NASA Langley Research Center Supersonic Lewis Res. United State; NASA, 1979: 347-356.
- [11] ZHANG Xin, LIU Baojie. Analysis of the core driven fan stage with compact aerodynamic configuration[J]. Journal of Propulsion Technology, 2011, 32(1): 47-53. (in Chinese)
- [12] ZHANG Xin, LIU Baojie. Analysis of the aerodynamic design of core driven fan stages[J]. Journal of Aerospace Power, 2010, 25(2): 434-442. (in Chinese)