Flow characteristics of the inlet in turboprop engine with the influence of sands

Mi baigang [1,2], Zhan hao [1,2], Yu jingyi [3]

[1]School of Aeronautics, Northwestern Polytechnical University, Xi 'an, 710072, China;

[2]National Key Laboratory of Aircraft Configuration Design, Xi'an, 710072, China;

[3]No. 5715 Factory of PLA, Luoyang, 471000, China

Abstract

The turboprop service environment is variable, and its inlet characteristics are affected by various foreign objects such as sand. In this paper, a numerical simulation method based on CFD-DPM for turboprop inlet characteristics under the influence of sand is constructed, taking the inlet with a bypass duct as an example. The effects of different sand particle concentration, particle incidence direction, incident velocity and other parameters on inlet performance parameters are investigated, and the interference characteristics of propeller slipstream are compared and analyzed. The results show that 10% volume fraction of sand has little effect on the total pressure recovery coefficient after entering the inlet, but the distortion rate increases by 3.2% due to the effect of the sand discrete phase of the mixed flow compared to the clean flow; The greater the incident velocity, the greater the influence of sand on the inlet flow characteristics, with the maximum difference in total pressure recovery coefficient up to 1.5% and the distortion rate up to 9%; When the incident direction is changed, the inlet flow stability of hybrid sand decreases, the maximum reduction difference of total pressure recovery coefficient reaches 0.868%, and the maximum increase difference of distortion rate is 9.8%. The propeller slipstream increases the inlet flow rate, although the mass flow rate increases, because it simultaneously accelerates the sand mixed in the airflow, increasing its ability to perturb. The total pressure recovery coefficient decreases by 2.52% and the distortion rate increases by 9% compared to the state without slipstream when the particle incident velocity is considered. The effect of increasing particle angle under the influence of slipstream is similar to that without slipstream.

Keywords: sand；turboprop；Intake；discrete phase；Computational fluid mechanics

1. Introduction

Turboprops have good environmental adaptability, and can take off and land normally under conditions such as grass, ice and snow ground, sand and gravel road and even dirt runway [1]-[2], so the application scenarios are diverse and the application fields are broad. Among them, when taking off from the gravel runway, due to the effect and impact of the landing gear and propeller on the sand and gravel ground, the turboprop inlet is in an extremely harsh operating environment, as shown in Figure 1. Although the sand particles are small compared to other foreign objects, if the concentration of sand in the air is excessive, it worsens the quality of the air entering the inlet, potentially affecting turboprop intake performance [3]-[5].

Figure 1 -Turboprop takes off in a sandy environment.

During the takeoff phase, the aircraft needs to accelerate to nose wheel raising speed as soon as possible to climb off the ground. At this time, the engine's power output requires very high intake air, and the air flow and quality should be as high as possible to ensure sufficient and stable thrust. Obviously, due to the close distance between the engine and the runway at this time, either the sand rolled up by the front landing gear during the sliding process or the sand generated by the rotating suction of the propeller will inevitably enter the inlet and affect its internal flow characteristics, resulting in fluctuations in the total pressure recovery coefficient and distortion rate at the inlet port outlet, which will affect the thrust characteristics of the aircraft. Therefore, in view of the influence of foreign bodies such as sand entering the inlet, many researchers have carried out evaluation and analysis through numerical simulation or experimental methods, obtaining results of interference of different sand parameters on the inlet characteristic [6]-[8]. However, most of these studies focus on helicopters or jet-powered aircraft, and few studies have been done on turboprop inlets under the influence of slipstream. On the one hand, the external flow conditions are complex after the propeller slipstream couple the sand particles, on the other hand, the internal flow characteristics of the turboprop inlets are highly specific due to the different turboprop inlet profile from conventional jets, whose use scenarios require consideration of adverse environmental requirements.

A typical turboprop inlet with a bypass duct is studied in this paper, and the internal flow characteristics of the inlet under the influence of sand are mainly considered. Sand is treated as a discrete phase based on the DPM model, coupled CFD method is used to carry out the effects of its motion collision after the airflow enters the inlet, and the effects of different sand conditions with or without propeller slipstream on the inlet performance are evaluated, providing a reference for evaluating the inlet design boundary and flight performance.

2. Computational model and simulation method

2.1 A typical turboprop inlet with a bypass duct

The object of this study is the turboprop nacelle configuration with a bypass duct, as shown in Figure 2 [8]-[10]. The intake system consists of an inlet duct, an outlet duct, and a bypass duct. The inlet is located behind the propeller and has an area of 0.16 m^2. A triple channel is formed at a distance of 2.5 m from the entrance, one connecting the inlet exit through the guide vanes and the other connecting the bypass channel. The bypass duct is a special outlet whose main purpose is to eliminate foreign object ingestion as much as possible during the operation of the system, and it can also be used for flow control when the intake volume is too large. According to the design requirements of this configuration, the maximum foreign object passing size of this bypass is no more than 0.20m × 0.11 × 0.01m.

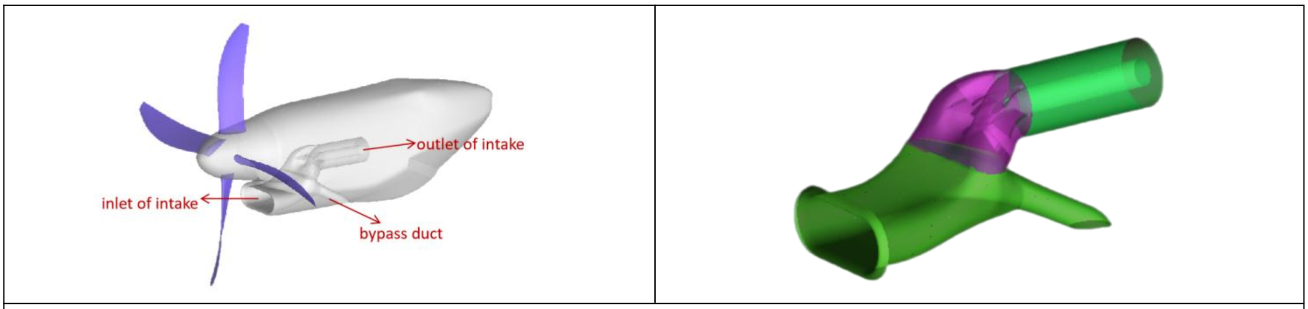


Figure 2 -A typical turboprop inlet with a bypass duct.

2.2 Diagrams and Figures Simulation method of effects of sand particles on turboprop inlet characteristics based on the DPM model

Sand is a discrete foreign object, sand ingestion test is also one of the subjects that must be completed in aero engine qualitative design. According to the requirements of relevant test specifications, quartz sand is adopted for general sand ingestion test, and its particle size is shown in Table 1. The engine and its components shall be capable of operating in a ground environment containing 0.053g of sand and dust per cubic meter, with a volume fraction of about 10% converted to the inlet configuration of the project, as required by the test specification.

Table 1 GJB2026 specifies the size and specific gravity requirements of sand for testing [11]

Size/um	1000	900	600	400	200	125	75
＜Specific gravity of sand of this size /%	100	98～99	93～97	82～86	46～50	18～22	3～7

Because the particle size of sand is different, Rosin-Rammler distribution function [12] is used to describe the particle size data specified by the national military standard, and the fitting formula is as follows：

$$F(d)=1-\exp[-(\frac{d}{0.3019})^{1.7724}]$$

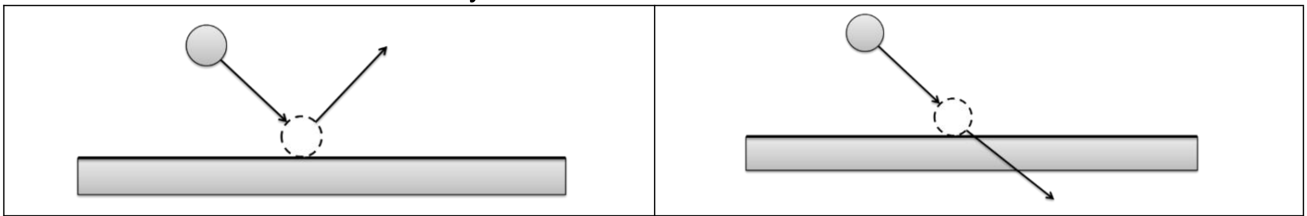
Because the sand is trapped in the atmosphere, its initial velocity is consistent with the free flow. Different from conventional foreign objects, sand particles are trapped in the air stream and enter the inlet. Although the volume is small, the distribution is random, and the volume fraction determines the quality characteristics of the air stream entering the inlet. In this paper, CFD coupled discrete phase model (DPM) [13] is used to study the effects of sand particles on the characteristics of the inlet internal flow, Turbulence model is selected as the model, which is widely used in internal flow simulation. Its equation is as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j})+G_k+G_b-\rho\varepsilon-Y_M+S_k$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j})+C_{1\varepsilon}\frac{\varepsilon}{K}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}R_\varepsilon+S_\varepsilon$$

$$C_{1\varepsilon}=1.42, C_{2\varepsilon}=1.68$$

When using a coupled discrete phase model simulation, it is necessary to ensure that the volume fraction of sand particles mixed in the airflow does not exceed 10%, with the aim of ensuring that the particles are independent of each other and there is no interaction. Sand particles are treated as rigid particles in simulation, and their interaction with the boundary of flow field is divided into two cases (Figure 3): 1) The particles rebound after colliding, that is. the sand particles rebound after colliding with the inlet internal wall, and the velocity of the bounce motion is obtained from the recovery coefficient set by the DPM model; 2) Particle crossing, that is, the sand particle crosses after it touches a non-wall boundary.



（a）sand rebound　　（b）sand crossing

Figure 3 -Sand-boundary contact condition.

The DPM model simplifies the moving particles as moving particles, modulates the particle shape and volume, and ignores the flow details around the particles (such as vortex shedding, flow separation, boundary layer, etc.) in the calculation. In actual simulations, particle drop locations are located on a virtual delivery surface in front of the inlet, as shown in Figure 4, in order to ensure particle concentration entering the inlet and improve computational efficiency. According to the premise of completely covering the inlet entrance, the particle release surface in this paper is located at 2 m of the inlet lip, and its radius is 1 m.

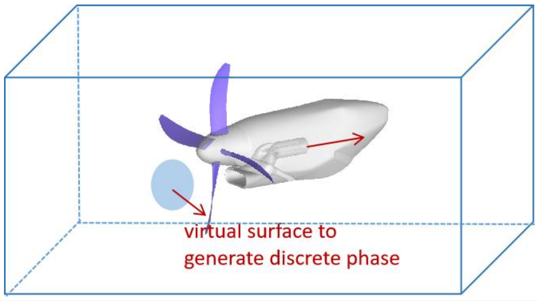
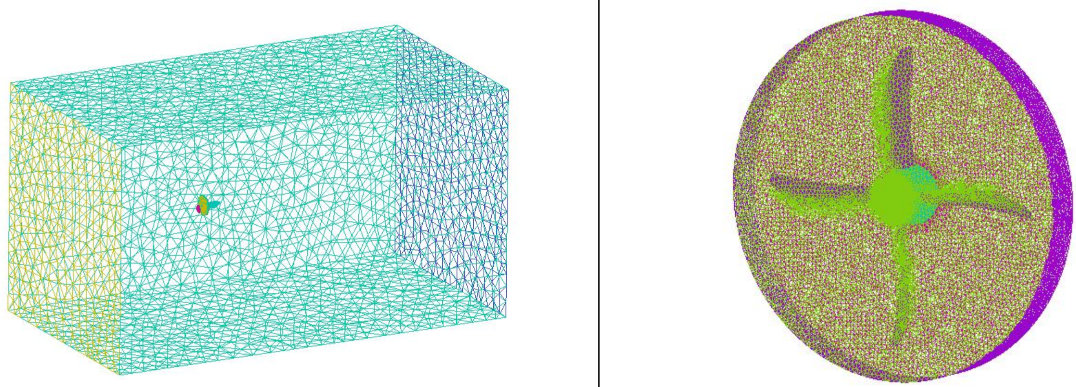


Figure 4 -Virtual particle drop surface.



（a）Stationary region

（b）Moving area grid

Figure 5 -Computational Grid.

3. Analysis of effects of blowing sand parameters on inlet characteristics without slipstream effects

When there is no slipstream effect, after the sand is released from the virtual delivery surface, the mixed incoming stream impacts into the inlet. Subsequently, due to the flow characteristics in the duct, the "motion-impact" phenomenon occurs in the interior of the inlet system (Figure 6), eventually entering the main engine interior or exiting from the bypass. Sand entering the main engine has a noticeable effect on the entire engine system, not only changing the airflow quality at the inlet exit, but also affecting overall efficiency due to entering the main engine components. In this paper, considering the actual flight situation, the interference effect of different sand concentration, particle size, incident velocity and direction on the inlet flow is studied, and the service boundary of the inlet form is evaluated under extreme wind and sand conditions.

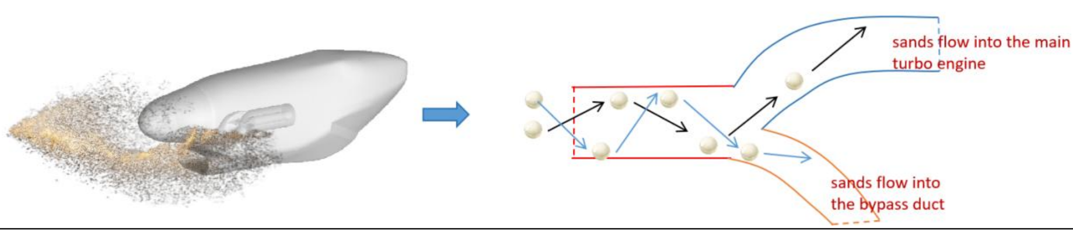


Figure 6 -Sand enters the inlet without slipstream effect.

3.1 Performance comparison of inlets after sand ingestion without slipstream effect

A 10% volume fraction of sand is generated from the virtual surface without the effect of slipstream, and the internal flow characteristics of the inlet system are evaluated using a BPM model. The calculated results are shown in table 2. The performance of the inlet is affected by the sand entering the inlet. Sand with a volume fraction of 10% increases the distortion rate by 3.2%, and decreases the total pressure recovery coefficient and exit flow by 0.85% and 3.55%, respectively. Figure 7 shows the schematic diagram of particle tracking when the calculated sand concentration is 10%. It is found that among the 300 particles tracked, 20 enter the bypass channel and the rest enter the main engine. The results show that the bypass plays a role of separating particles, of course, because the suction effect of the bypass is not considered in the calculation model in this paper, and the bypass also has its own total pressure recovery coefficient and other indicators. If this condition is added, the effect of separating the foreign object may be more pronounced. The effect of sand on the inlet performance is mainly reflected in the distortion of the airflow. Because the particles are mixed into the airflow, the airflow uniformity is changed, and the friction with the gas constantly consumes energy in motion. Therefore, the local airflow quality characteristics are greatly changed. Figure 8 shows the total pressure distribution of the characteristic section without sand in the incoming flow and with 10% sand by volume, from which the effect of sand concentration on inlet performance can be seen more clearly.

Table 2 Effect of sand on inlet flow characteristics without Slipstream

	the distortion rate ε（%）	the total pressure recovery coefficient σ	Inlet exit mass flow kg/s	Entry main engine particle fraction	Entry bypass exclusion particle fraction
Without sand	2.19	0.982426	12.936	——	——
10% sand by volume	2.26	0.974055	12.476	93%	7%

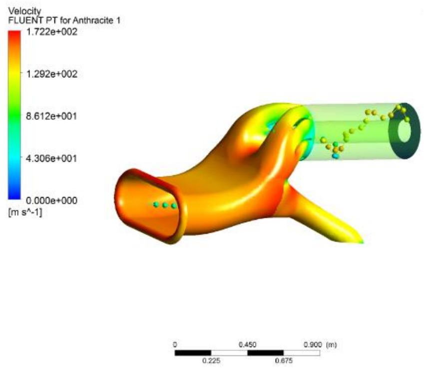
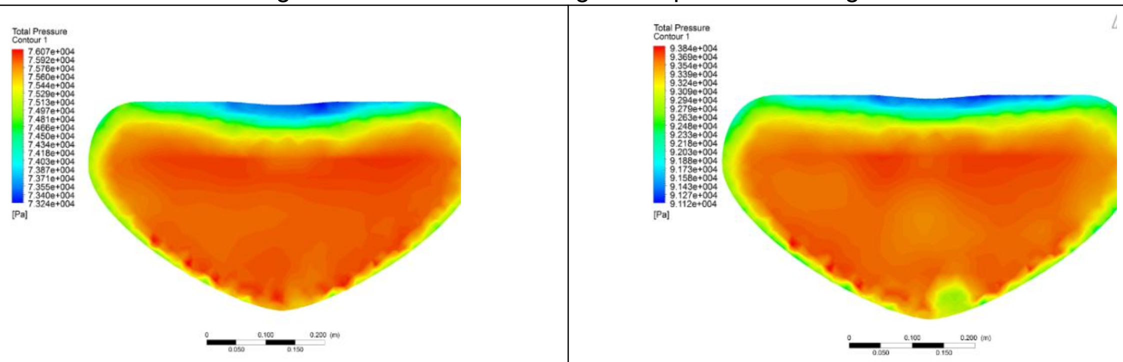


Figure 7 -the schematic diagram of particle tracking.



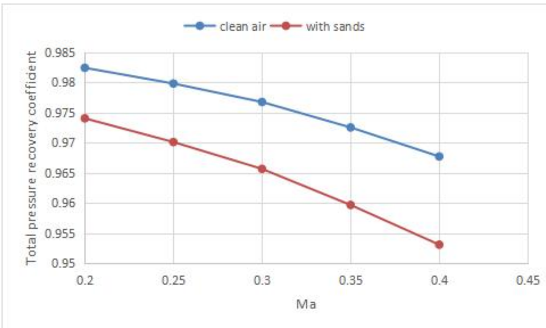
(a) No foreign object interference | (b) 10% sand by volume

Figure 8 -Effect of Sand on total pressure distribution of a typical section without the effects of slipstream.

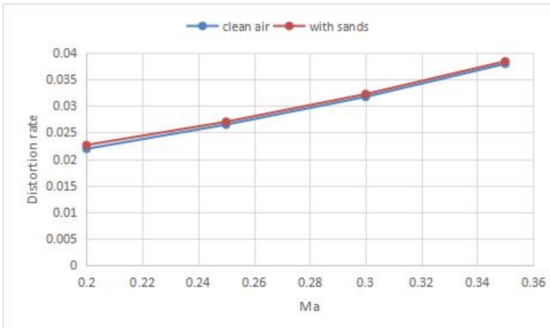
3.2 Analysis of influence of sand ingestion parameters on inlet performance

Although the volume of sand particles is small, the sand particles are mixed in the incoming flow into the inlet, on the one hand, the uniformity of the air flow is affected, and on the other hand, the wall surface is eroded because of the roughness. In this paper, the parameters such as the incident velocity and direction are analyzed. The volume concentration of sand is set to 10%, in which the incident velocity is changed by adjusting the incoming flow velocity, and the incident direction only requires changing the angle of the incoming flow. Figure 9 shows the change in total pressure of the characteristic surface (the heart surface of a three-way pipe) at different sand particle incident velocities. It can be seen that the mass flow rate at the same time basically presents a linear increasing trend with increasing incident velocity. As the mass flow rate with sand particles mixed in the incoming stream decreases, the percentage reduction in mass flow rate will stabilize around 3.5% with the increase of the incident velocity. Total pressure recovery coefficient decreases with increasing incident flow rate, and the difference in total pressure recovery coefficient with and without sand interference at Ma=0.4 increases by about 7% compared to Ma=0.1. The main reason for this is that although the flow rate increases after increasing the velocity, the heart surface is located at the inlet bypass junction, the flow of mixed sand particles will enter the main engine or bypass at the junction area, so the rejection effect of the bypass is enhanced after increasing the flow rate. In this article, the monitored bypass exhaust particles increase from 20% of the incident velocity Ma=0.2 to 37% at Ma=0.4, so the total pressure is lost. The distortion rate increases with the increase of the velocity of the mixed sand flow, which reflects that the disturbance of the characteristic surface is more intense after the particle energy is enhanced. The distortion rate of flow with and without sand disturbance decreases with the increase of incident velocity, which may be due to the enhancement of local disturbance by sand particles after the increase of airflow velocity. It makes up the difference between maximum and minimum total pressures on the entire characteristic surface. Figure 11 shows the variation of flow field characteristics at different incidence angles of sand particles. From the perspective of configuration, the characteristic surface of the three-way pipe of this project has a certain angle with the horizontal plane, and the change of particle incidence angle also changes the relative angle between the air flow and the characteristic plane. As the angle of incidence increases, it is more parallel to the characteristic surface, so the total pressure recovery coefficient, distortion rate, and flow characteristics are improved. Compared with the calculation condition with or without sand disturbance, because the volume fraction content is fixed, the difference between total pressure recovery coefficient and mass flow rate is basically stable, with total pressure recovery coefficient difference of about 0.86% and mass flow rate difference of about 3.5%. However, the distortion rate varies significantly with the angle of incidence, as the flow tilt causes the particle to collide and rebound inside the inlet after the angle of incidence increases. The larger the angle of incidence, the more intense the particle motion collision in front of the crossing feature, and thus the effect on the local total pressure is more obvious. When the incidence angle is increased from 0 to 12 degrees, the difference in the distortion rate of characteristic surfaces with and without sand particles increases from 3.2% to 9.8%.

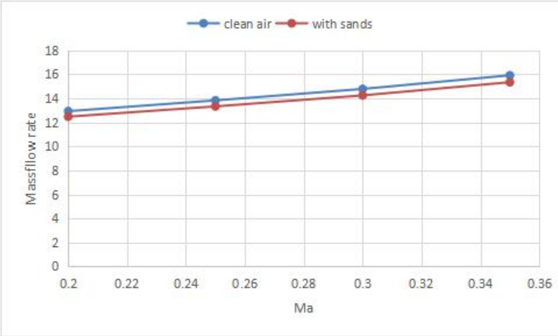
Figure 12-13 shows the total pressure distribution of the inlet section with sand at different incident velocities and angles. It can be seen that the impact of the incident velocity on the overall internal flow characteristics is not as obvious as that of the incident angle. The large incident angle changes the direction of the air flow and has obvious disturbance to the high and low regions of the total pressure.



（a）Total pressure recovery coefficient



（b）The distortion rate



（c）Mass flow

Figure 9 -Effect of sand particle incident velocity (at an angle of attack of 0°).

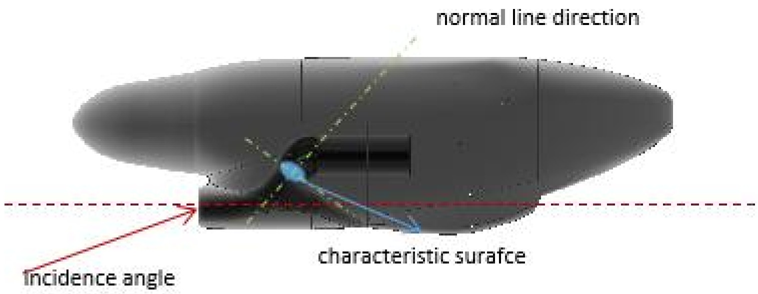
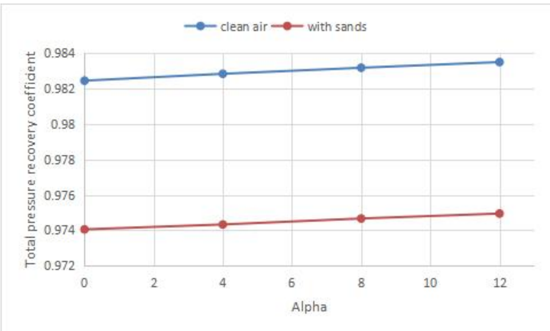
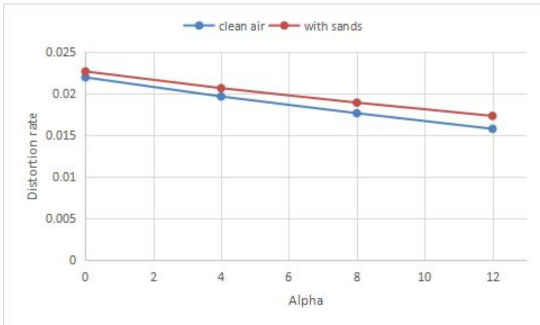


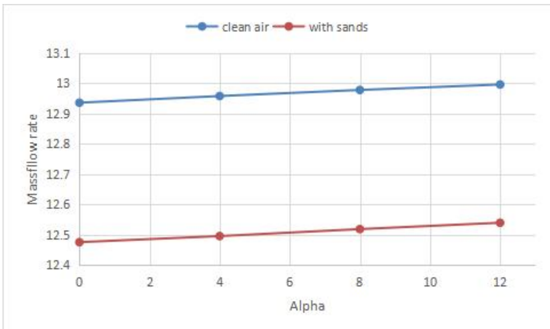
Figure 10 -Relationship between incidence angle and characteristic surfaces.



（a）Total pressure recovery coefficient

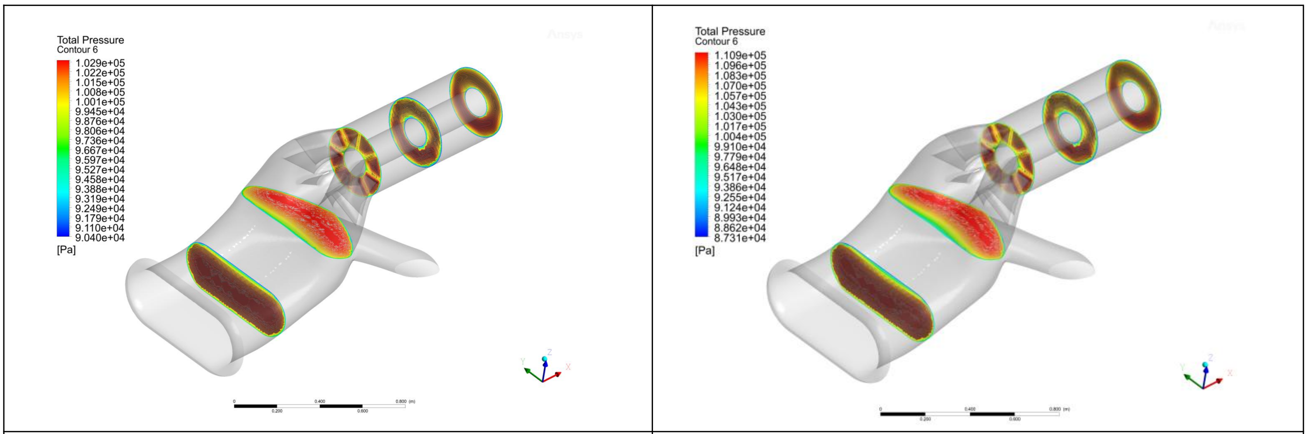


（b）The distortion rate



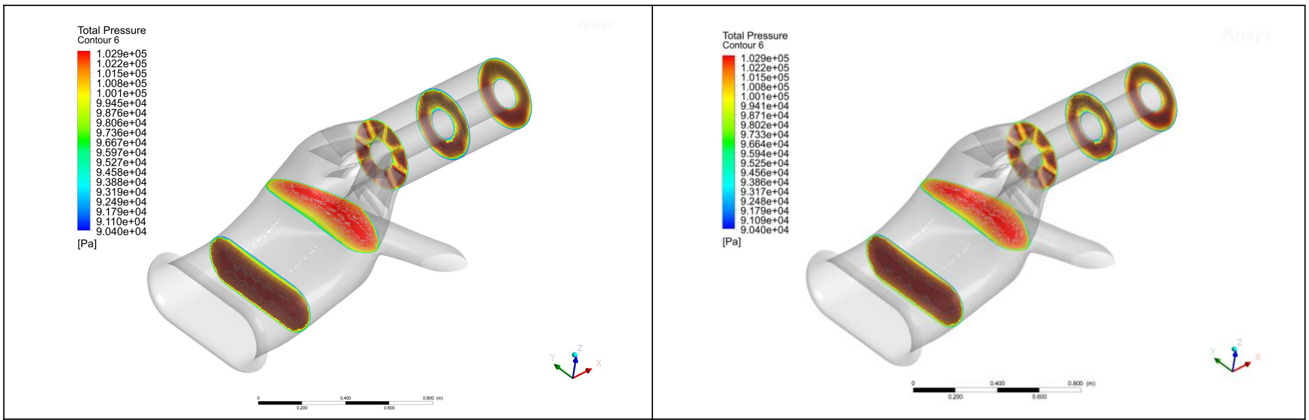
（c）Mass flow

Figure 11.- Effect of angle of incidence of sand particles (Ma=0.2）.



（a）Ma=0.2　　（b）Ma=0.4

Figure 12 -Total pressure distribution inside the inlet at different incident velocities.



（a）alpha=0°　　（b）alpha=12°

Figure 13 - Total pressure distribution inside the inlet at different incidence angles.

4. Analysis of effects of blowing sand parameters on inlet flow characteristics with propeller slipstream

The initial state of the sand entering the inlet changes as the propeller rotates. On the one hand, some of the sand hits the propeller blades bouncing off the inlet and cannot enter the inlet, on the other hand, the sand behind the propeller is affected by slipstream to produce rotation and acceleration effects (Figure 14). At this time, the flow-sand two-phase flow characteristics at the inlet are different from those without slipstream, so the movement and exclusion characteristics of sand particles in the entire inlet are also different. In this paper, according to the actual engine dynamic characteristics, the propeller working parameters are set, and the induced effect of slipstream on the effect of sand entering the inlet is analyzed.

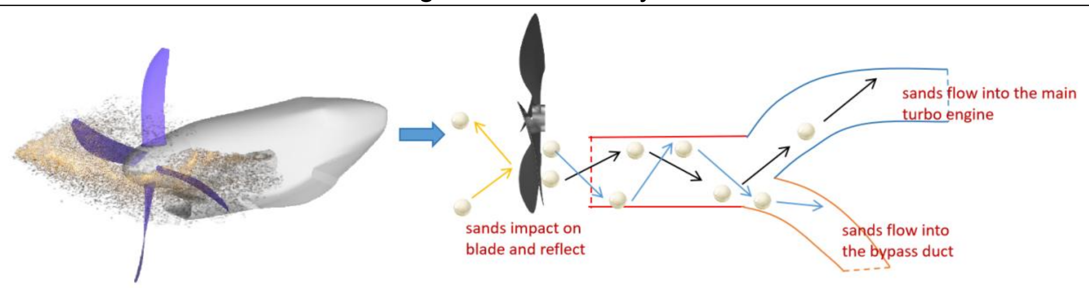


Figure 14 - Sand enters the inlet with slipstream effect.

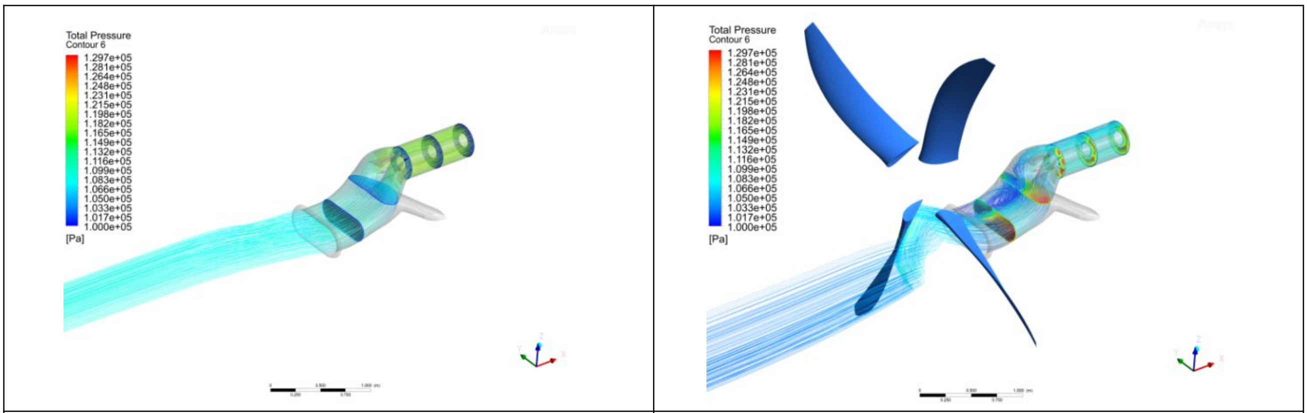
In this paper, the propeller speed is set to be 3000 r/min according to the actual situation in low speed flight. Since the propeller slipstream needs to be evaluated using the unsteady calculation, the simulation results of the flow characteristics in the characteristic surfaces in this paper are all time averaged.

4.1 Internal flow characteristics of a sand free inlet considering propeller slipstream

Inlet characteristics with and without propeller slipstream effects are shown in Table 3. It is clear that the inlet mass flow rate is improved due to the acceleration of the slipstream, which makes the flow into the inlet greater at the same flight speed. However, the rotation effect increases the non-uniformity of the flow entering the inlet, so the distortion rate, which represents the flow equilibrium of the characteristic surfaces, increases significantly and the total pressure recovery coefficient decreases slightly. From the flow field diagram inside the inlet given in Figure 15, it can be clearly seen that the increase in the degree of non-uniformity of the air flow on the monitored section. Therefore, it is necessary to pay close attention to the rise of total pressure distortion caused by slipstream for propeller aircraft.

Table 3 Effect of propeller slipstream on inlet internal flow characteristics without sand effect (Ma=0.2, at an angle of attack of 0°, propeller speed 3000 r/min)

	the distortion rate ε（%）	the total pressure recovery coefficient σ	Inlet exit mass flow kg/s
without propeller slipstream effects	2.19	0.982426	12.936
with propeller slipstream effects	8.85	0.97977	14.566



(a) without propeller slipstream	(b) with propeller slipstream

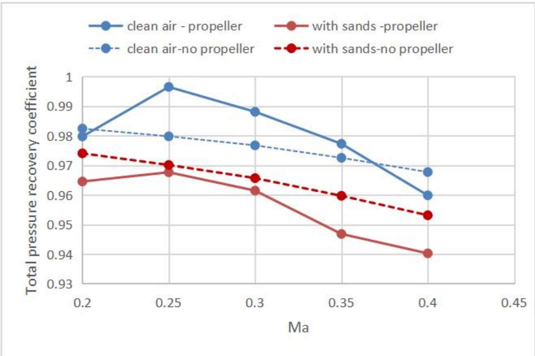
Figure 15 - Inlet internal flow lines with and without propeller slipstream.

4.2 Analysis of influence of sand ingestion parameters on inlet performance with propeller slipstream

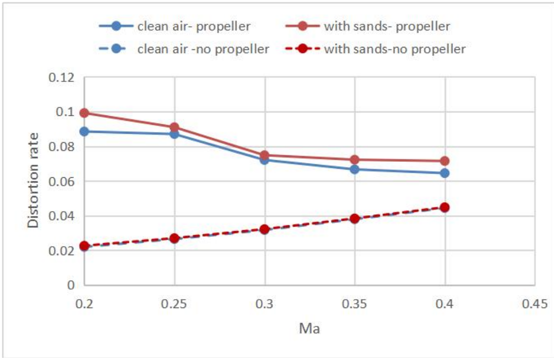
Figure 16 – 17 shows the simulation results of propeller slipstream interference with inlet internal flow characteristics at different particle incidence velocities and angles, respectively. When the particle incidence velocity increases, it means that the number of particles entering the inlet increases, but rebound off hitting the propeller blades are also more serious. The ratio of bouncing particles hitting the propeller increased from 17% to 25% at the angle of attack of 0°, compared with simulations at Mach 0.2 and 0.4. However, there was a significant increase in the absolute amount of sand inside the inlet at Mach 0.4 due to the increased flow rate. Therefore, after considering the influence of slipstream, with the increase of incident velocity, the increase of particle number on the characteristic surface affects the overall total pressure of the flow, showing a decreasing trend in the coefficient of total pressure recovery coefficient. The total pressure recovery coefficient of the characteristic surface at Mach 0.4 decreases by 2.52% compared to Mach 0.2. For the distortion rate, although sand particles mixed into the airflow affect the local total pressure distribution, the effect of sand particles is not obvious compared with the gradient change caused by the rotation effect of the propeller slipstream, and its primary role is reflected on the propeller. As the incident velocity increases, the overall distortion rate decreases instead, mainly due to the reduced proportion of the rotational velocity component of the propeller slipstream compared with the incident velocity, and the greater energy distribution downstream of the airflow

entering the inlet, so the local total pressure non-uniformity is weakened. It can also be seen that slipstream and sand particles actually produce a mutually deterioration of the inlet internal flow, increasing the maximum total pressure distortion rate by 9% compared with that without slipstream.

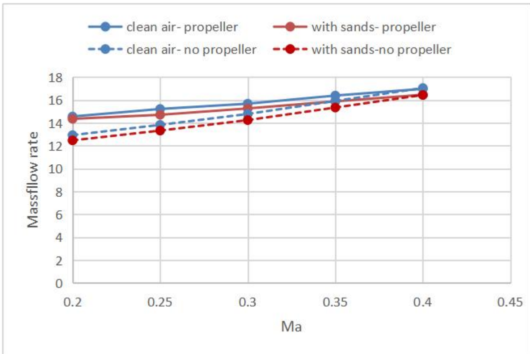
The law of incidence angle influence is basically similar to that of a clean atmosphere without sand. The total pressure recovery coefficient increases with the angle of incidence. When sand particles are mixed into the air flow, the quasi-linear increase law of the total pressure recovery coefficient becomes strongly nonlinear. the total pressure recovery coefficient is slightly larger at small incident angles without slipstream; At high angles of incidence, the total pressure recovery coefficient of states with slipstream effects is greater, which is mainly caused by the greater component of the velocity of the slipstream perpendicular to the characteristic plane direction. For total pressure distortion, slipstream makes the distortion gap between the presence and absence of sand larger, while the mass flow rate increases slightly with increasing incidence angle.



（a）Total pressure recovery coefficient

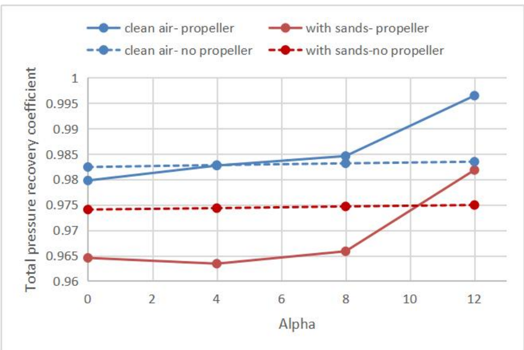


（b）The distortion rate

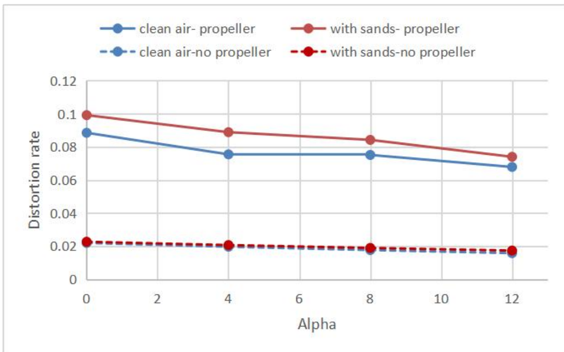


（c）Mass flow

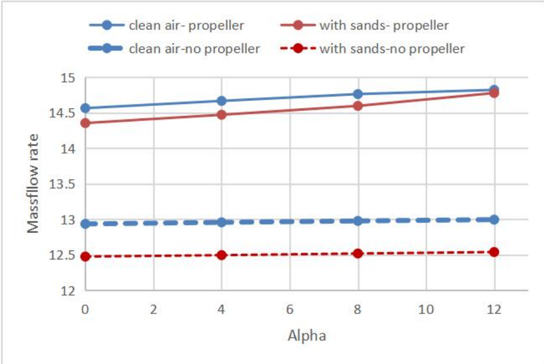
Figure 16 - Inlet characteristics of different particle incident velocities under the influence of slipstream(at an angle of attack of 0°).



（a）Total pressure recovery coefficient

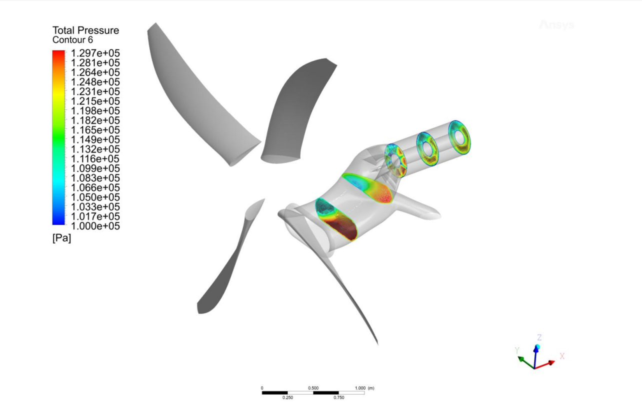


（b）The distortion rate

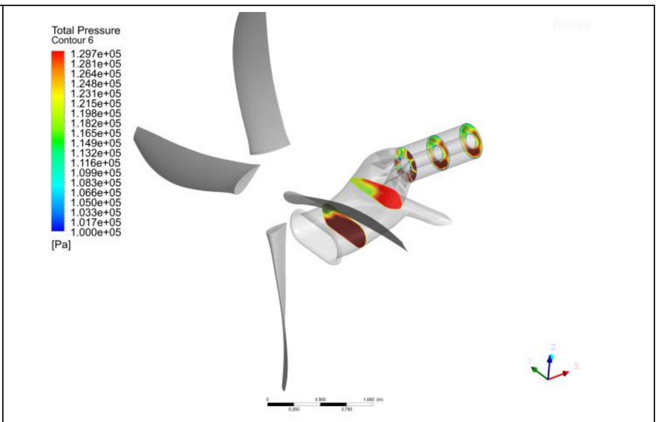


（c）Mass flow

Figure 17 - Inlet characteristics of different particle incident angles under the influence of slipstream(at an angle of attack of 0°).

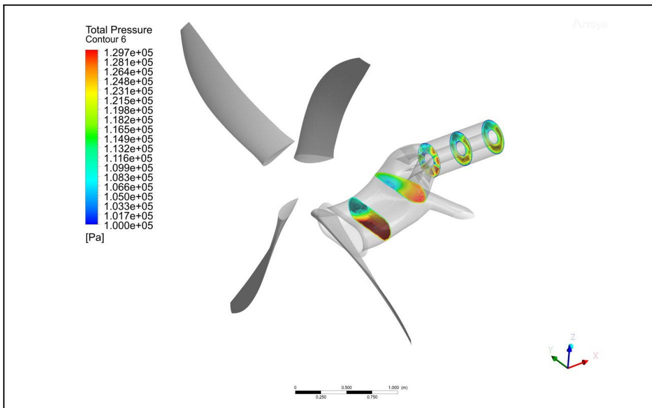


（a）Ma=0.2

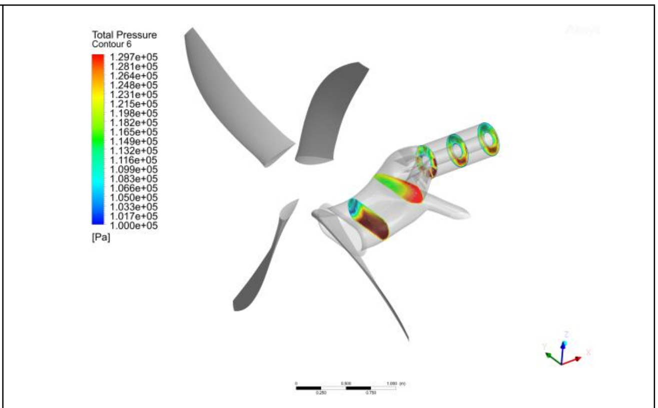


（b）Ma=0.4

Figure 18 - Total pressure distribution inside the inlet at different incident velocities.



（a）alpha=0°



（b）alpha=12°

Figure 19 - Total pressure distribution inside the inlet at different incident angles.

5. Conclusions

In this paper, the change of internal flow characteristics of turboprop engine inlets with and without slipstream is analyzed, and the flow variation phenomena of turboprop inlets in sandy environment are combed. Based on the CFD-DPM model, the numerical simulation method of turboprop inlet flow field with and without slipstream effects is constructed, the quality characteristics of inlet flow field with and without slipstream effects are studied, and the effects of different sand parameters (concentration, incident velocity, size, etc.) on the inlet are obtained. The research in this paper can provide support for turboprop inlet design and airworthiness verification.

6. Conflict of interest

The authors declare that they have no conflict of interest.

7. Acknowledgement

The authors would like to acknowledge the support of National Natural Science Foundation of China (Grant No. 12202363) , the Key Laboratory Fund (Grant No.D5150240005) and the support of Natural Science Foundation of Chongqing(Grant No.CSTB2023NSCQ- MSX0042).

8. Copyright Statement

References

[1] Ashenden R, Marwitz J D. Turboprop Aircraft Performance Response to Various Environmental Conditions[J]. *Journal of Aircraft*, 1997, 34(3):278-287

[2] Kirmizi M, Aygun H, Turan O. Performance and energy analysis of turboprop engine for air freighter aircraft with the aid of multiple regression[J]. *Energy*, 2023, 283:1-11

[3] Bojdo N, Filippone A, Parkes B, et al. Aircraft engine sand ingestion following sand storms[J]. *Aerospace science and technology*, 2020, 106:106072.1-10

[4] Maynard W L, Sand W R. State of the Art Knowledge for Icing Accidents for General Aviation Aircraft, The[J]. *Journal of Air Law & Commerce*, 2000, 64(2):279-281.

[5] Saeed F, Al-Garni A Z. An inverse design method for aircraft engine sand separator system[J]. *Aeronautical Journal*, 2012.

[6] Tang J, Xie Y, Zhu J, et al. Numerical and experimental investigations into protection net icing at the helicopter engine inlet, *Aircraft Engineering Aerospace Technology*, 93 (2021) 1513-1525.

[7] Costes M, Moens F. Advanced numerical prediction of iced airfoil aerodynamics, *Aerospace Science Technology*, 91 (2019) 186-207.

[8] Mi B G, Zhan H. Numerical Simulation on Rigid Foreign Object Exclusion in the Turboprop Engine Intake System with a Bypass Duct[J]. *IEEE Access*, 2019, 7(99):61920-61933.

[9] Ooba Y, Murooka T, Yamane T, et al. Experimental and Numerical Research of Fan Bypass Duct Flows in Japanese Environmentally Compatible Engine for Small Aircraft Project[C]. *ASME*，2011.

[10]George W M. Extension of Particle Image Velocimetry to Full-Scale Turbofan Engine Bypass Duct Flows[D]. Blacksburg, Virginia, 2017.

[11]GJB 2026-1994. Test of sand ingestion, aircraft turbojet and turbofan engine, requirements for[S]. Commission of Science, Technology and Insandry for National Defense, 1994.

[12]Brown W K, Wohletz K H. Derivation of the Weibull Distribution Based on Physical Principles and its Connection to the Rosin-Rammler and Lognormal Distributions[J]. *Journal of Applied Physics*, 1998, 78(4):2758-2763.

[13]Li, Chao L.CFD-DPM Modeling of Gas-Liquid Flow in a Stirred Vessel[J]. *Advanced Materials Research*, 2012, 550-553:979-983.