A CONCEPTUAL ANALYSIS OF AN AIRCRAFT WITH REAR-MOUNTED OPEN ROTOR ENGINES

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Abstract

This article presumes the blooming development of open rotor engines that will power the new generation of airliners, describes the primary problems that need to overcome for open rotor engines, such as noise shielding problem, blade out or rotor burst problem, bird strike or debris strike problem. After the analysis of combination between BWB and Open rotor engines, this article prefers the integration of open rotor engines with relative conventional configuration aircrafts, then proposes 2 concepts of integration configurations, which can be classified into wing mounted configuration and rear mounted configuration. After the qualitative descriptions of advantages and disadvantages of each concept, this article uses a CFD model to analyze the aerodynamic interaction for wing mounted and rear mounted configuration, finally declares the most promising configuration of open rotor aircraft that will enter into civil aviation market in the next ten or twenty years.

1 Open rotor engine configuration

An open rotor engine or propfan is a type of aircraft engine related in concept both the turboprop and turbofan, but distinct from both. The engine uses a gas turbine to drive two lines of contra-rotating propeller in order to balance the running torque. According to the forward or rear locations of the propellers or fans, there are mainly two types of open rotor engines: puller configuration and the pusher configuration, as in Figure 1and Figure 2. Both configurations have their own characters. Puller configuration can use the blades as a compressor of the inflow of engine. while pusher configuration puts the unducted blades right connected outside the turbines, there is no necessary for a shaft to transfer the torsion moment to front propellers (not compressor), so pusher configuration shows a relative simple structure and has more advantages for weight saving.

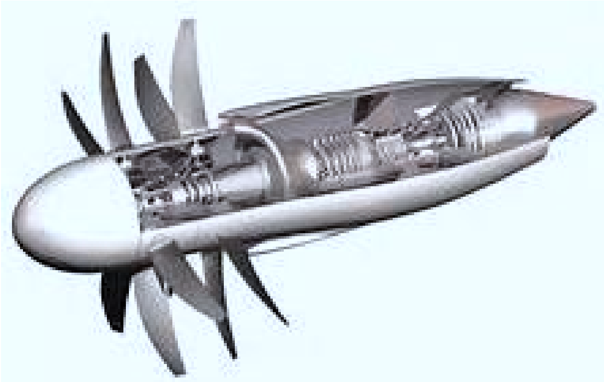

Fig.1 Puller configuration of Open Rotor

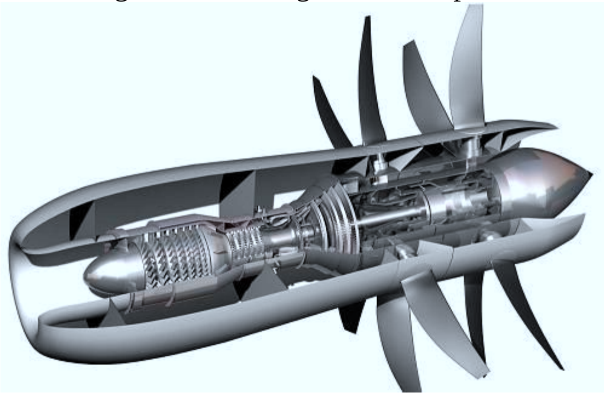

Fig.2 Pusher configuration of Open rotor

New generation of engine powers the new generation of aircraft. There are plenty of studies conducted by NASA and Boeing company show that open rotor engine is suitable for aircrafts of flying wing configuration or blended wing body (BWB or HWB, Hybrid Wing Body). In this configuration as shown in Figure 3[1], engines can be installed on the upside of rear body, which can use the whole wing body to reduce the noise propagating to ground, thus satisfy the community noise requirement. However, because of this particular configuration, the lever length of empennage is short compared with the conventional fuselage and wing. The trimming ability of empennage is restricted. Thus the longitudinal momentum of airfoil and the full aircraft should be taken into account during the aerodynamic design. It is mostly likely that the BWB configuration should first be applied in UAC (Unmanned Aerial Vehicle) and cargo transport. In contrast, the conventional configuration airliner with open rotor engines is very likely to enter into service in the next decade. So this article focuses on the integration concept between conventional configuration and open rotor engines.

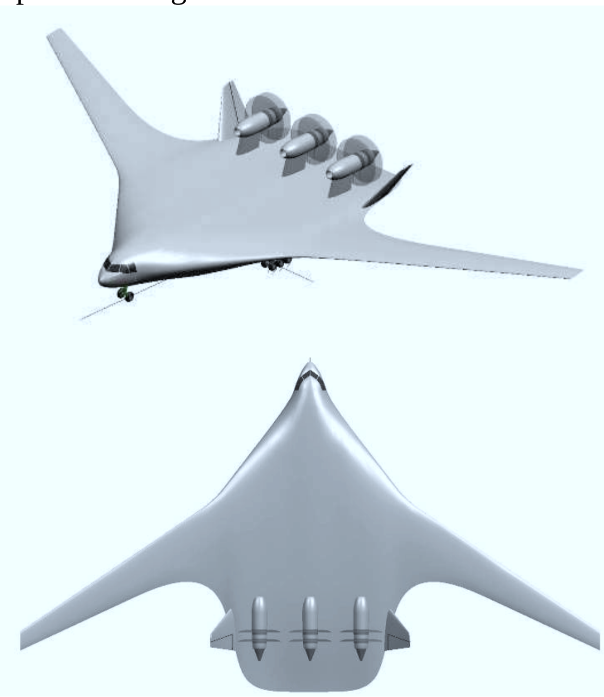

Fig.3 BWB with Open Rotor Engines

2 Open Rotor Integration with Aircraft

2.1 Conventional Configuration with Open rotor engines

Nowadays the conventional configuration dominates the narrow body airliner and the wide body airliner, which includes fuselage with almost circle sections, either a low wing or high wing connected to fuselage, with big sweep angle and big aspect ratio, HTP and VTP located separately on the rear fuselage. As the cruise speed is relatively slow, the output power is relevant small, the first generation of open rotor engine will most likely be introduced on narrow body airliner or single aisle airliner. Correspondent to the two specific configurations of open rotor engines, there are mainly two types of engine installation as shown in Figure 4 and Figure 5: wing mounted configuration and rear mounted configuration[2];

Fig. 4 Wing mounted configuration

Fig. 5 Rear mounted configuration

To generate the same level of thrust or power, the size of open rotor fans is between turbofan engine and turboprop engine, the diameter of open rotor is almost twice the size of turbofan engine[3]. Following the same way of turboprop engines, open rotor of puller configuration is suitable for wing mounted aircraft, while open rotor of pusher configuration is suitable for rear mounted aircraft, as shown in Figure 5. The following part will present discuss their own advantages and disadvantages.

2.3 Wing mounted configuration

The first concept of open rotor integration is wing mounted configuration as shown in Figure 6. In order to have enough space for propfan installation, wing mounted aircraft usually has a high wing configuration. High wing configuration usually accompanies with T-tail, to avoid the turbulent wake flow of the wing. There are both advantages and disadvantages for this configuration, the biggest advantage is that this configuration is conventional and mature, which make it easier to design and validate. Also in this configuration, the inflow of engine is free of interference; the engine can alleviate the bending load of the wing.

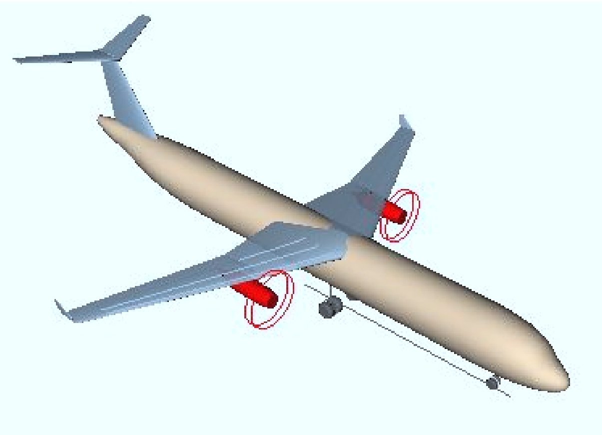

Fig.6 Wing mounted configuration

However, the biggest disadvantage can be the cabin noise. As the noise of open rotor engine is louder than turbofan, and the noise propagation direction is perpendicular to the engine axle, wing mounted open rotor engine is close to most part of passenger cabin, thus the cabin comfort cannot compete with rear mounted configuration. The blade dropped out from the open rotor may strike directly into cabin or oil tank, without the protection of nacelle, the risk can be fatal for safety; As the bird strike emerged as a concern for open rotor integration[4], the forward part of aircraft will cause higher risk of bird strike than the backward part installation; Moreover, the main landing gear is installed on fuselage, making the track of MLG is shorter and the risk of rollover is higher. Finally, because the slipstreams effect must be considered in wing aerodynamic design, this increases the difficulty in wing design. As s result, high wing aircraft is mostly operated and served as cargo transport or military aircraft.

2.4 Rear mounted configuration

In contrast to wing mounted configuration, rear mounted aircraft can integrate the open rotor engines with low wing and keep the benefit of low wing. To make the space for engine installation, rear mounted aircraft usually applies a T-tail configuration, as shown in Figure 7, it also prevent the horizontal tail from the propeller slipstream influence of the engine.

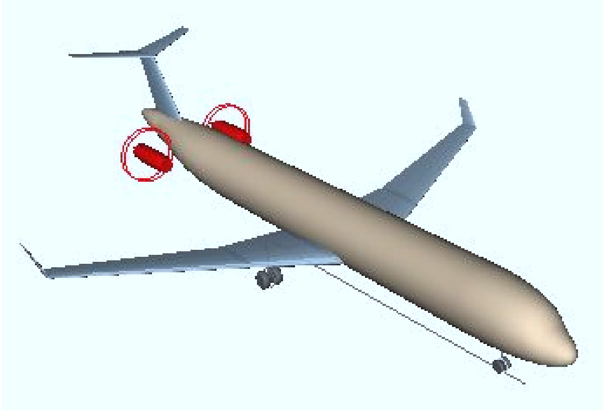

Fig.7 Rear mounted configuration

Most of passenger aircrafts apply a low wing configuration, thus the design and validate technique is mature and reliable. The low wing is more convenient for engine maintenance and repair. It can also absorb the kinetic energy during emergency landing, supply extra buoyancy force after ditching. Besides, rear mounted open rotor located far away from the most part of cabin, and the slipstream flow of engine has no influence to the aircraft, both can decrease the noise level of the cabin. In case of blade dropped out of open rotor, there is no risk for blade strike into cabin or tank. As the two engines located each side of rear fuselage, the possibility that blade dropped out of one engine to hit another is negligible, thus reduce the risk of all engine failure. Because of the rear location of open rotor, the risk of bird strike is lower while the risk of debris strike is a little higher. Besides, the clean configuration of wing avoids the wing from the open rotor slipstream effect, helps to achieve the best aerodynamic performance of wing design. Compared with the benefit of this configuration, the disadvantage is not much. Finally T-tail has the deep stall phenomenon, which should be taken special care.

3 CFD Analysis of engine integration

To analyze the aerodynamic impact to the aircraft characteristics due to the introduction of open rotor engines, this research began with a simple CFD model of a narrow body aircraft. This article used this model to analyze the difference between turbofan engine and open rotor engine. For turbofan engine analysis, this article use a through flow nacelle and stream tube area ratio to simulate the engine inflow rate and the impact to nearby airflow; As for open rotor engine analysis, this article use actuator disk model[5] to simulate the open rotor engines and the aircraft together, focus on the propeller slipstreams impact to aerodynamics like lift to drag ratio, longitudinal stability characteristics. Two representative configurations are compared with turbofan and open rotor engines: Wing mounted configuration and rear fuselage mounted configuration.

The aircraft chosen for the study is of 200 seats number level with single aisle, the configuration use a low wing and a T-tail. The wing span of this aircraft is 36 meters, and the max diameter of open rotor is around 4.4 meters. Figure 8 and Figure 9 show the surface mesh model for full aircraft with wing mounted and rear mounted turbofan engine. To simplify the mesh model and save the resource of calculation, the pylon and winglet are not included in this model.

3.1 Open rotor simplification

Based on momentum theory, actuator disk theory makes further simplification of propeller, it introduces a non thickness definite disk to simulate the momentum change after the propeller[6], thus the flow details around the blades are ignored, the axial drag and circumferential drag of blades are expressed by axial velocity and tangent velocity distribution along the circumferential direction shown in Equation (1):

$$\begin{cases} v_a(r) = \dfrac{\Delta H(r)}{V_0} \\ v_t(r) = V_0 \tan(\Delta\varepsilon(r)) \end{cases} \tag{1}$$

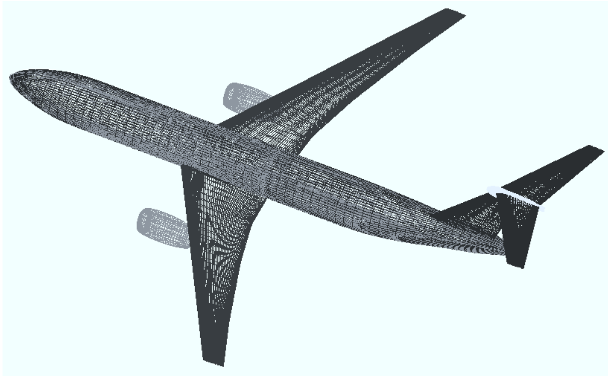

Fig.8 Wing mounted mesh model

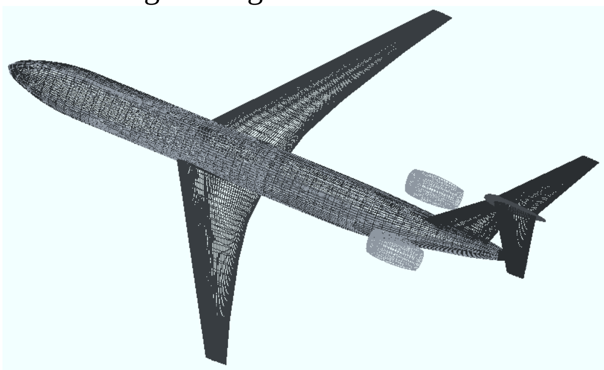

Fig.9 Rear mounted mesh model

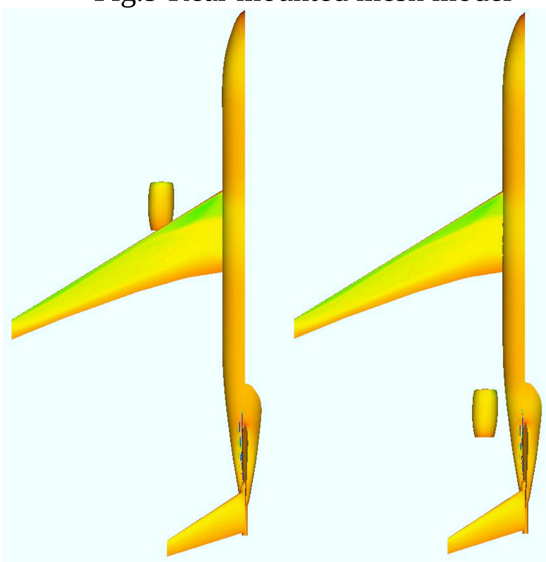

Fig.10 CFD pressure distribution

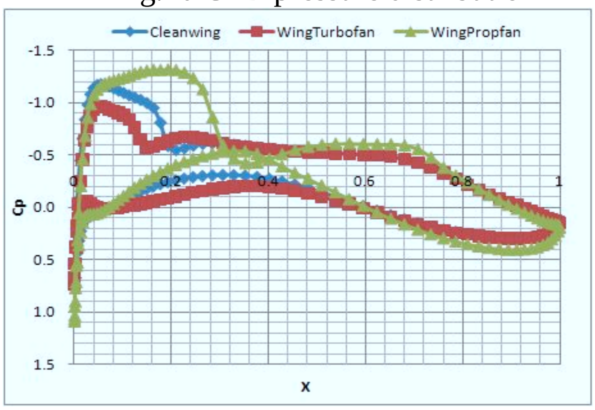

Fig.11 Cp distribution on section η=0.35

As shown by Figure 10, the wing mounted engines have apparent influence on wing section close to nacelle, while rear mounted engine has few impact on tail and wing. As for wing mounted turbofan engine, there is a trend to decrease the suction peak area. This trend is more clearly shown in Figure 11, with datum of clear wing, wing turbofan engine decreases the suction area while open rotor engine incline to increase the suction leading edge area, moves the shock wave backward.

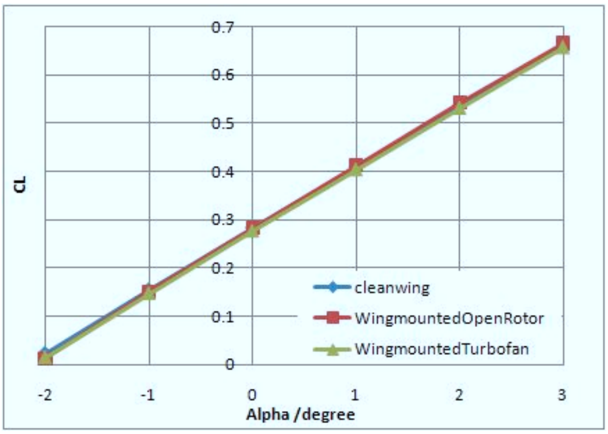

Fig.12 CL-AoA of wing mounted config

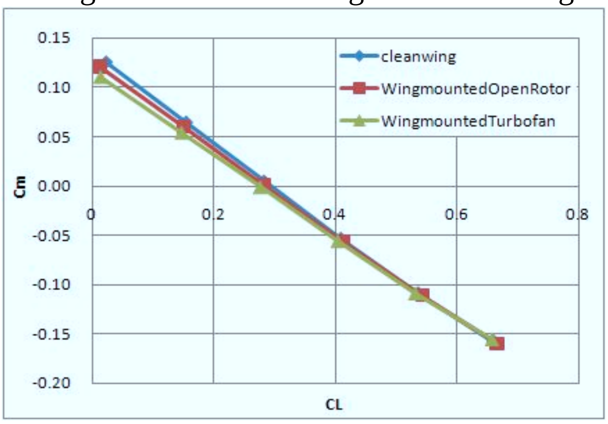

Fig.13 Cm-CL of wing mounted config

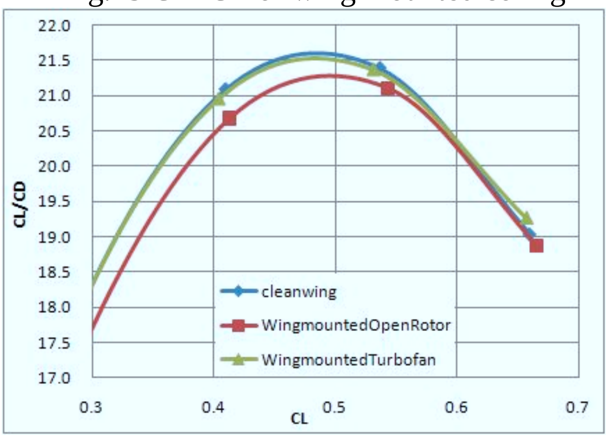

Fig.14 CL/CD of wing mounted config

As shown in Figure 12 and Figure 13, wing mounted engines have little influence on lift curve while trend to decrease the Cm-CL curves slope, which will decrease the longitudinal static stability margins. Wing mounted turbofan engines reduce more longitudinal stability margin while wing mounted open rotor decrease the optimum lift to drag ratio apparently.

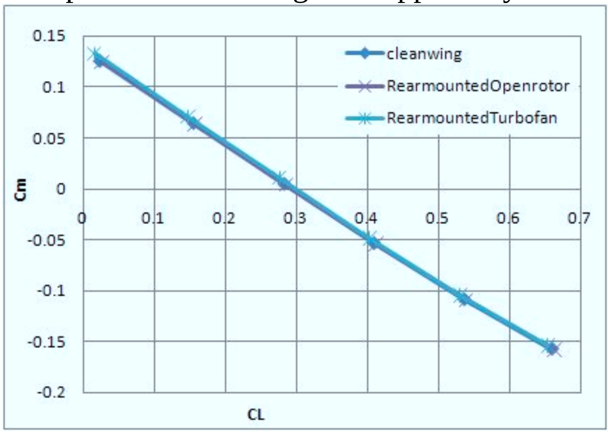

Fig.15 CL/CD of rear mounted config

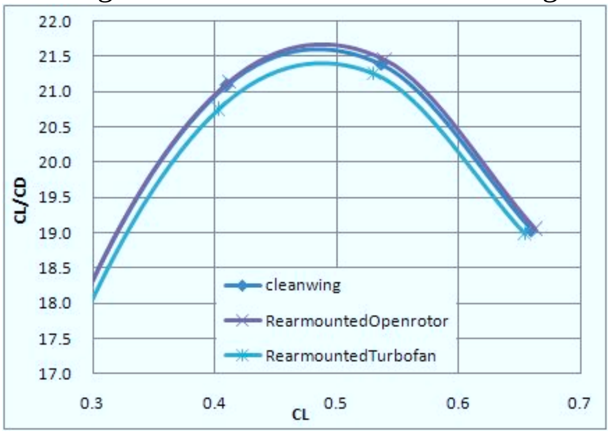

Fig.16 CL/CD of rear mounted config

As for rear mounted engines shown in Figure 15 and Figure 16, both turbofan engine and open rotor engine have little influence on longitudinal stability margin. Rear mounted turbofan engine decrease the optimum lift to drag ratio with a certain extent, while rear mounted open rotor engine have less influence. Talking about the aerodynamics, it is easy to conclude that rear mounted configuration is preferred by open rotor engines.

4 Conclusions

Research shows out that the biggest benefit of open rotor engine is to raise the bypass ratio, so as to decrease the specific fuel consumption, which can reduce the fuel burning and carbon exhausted. While the biggest concerns are in field of noise and safety problem including noise requirement, blade out or rotor burst certification, bird strike and debris strike certification etc. The engine mounted aircraft configuration plays an important role in noise shielding effect. Compared with wing mounted configuration, rear fuselage mounted configuration can alleviate the cabin noise and community noise apparently. In addition, rear fuselage mounted configuration avoid the risk of blade released to hit the fuel tank or cabin, the rear fuselage can act as a shield to protect blade out from one engine to destroy the other. In general, as the best compromise between economic, comfort and safety, rear fuselage mounted open rotor aircraft is the most promising configuration that enters into market in the next ten or twenty years.

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