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PARAMETER ANALYSIS ON CIRCULATION CONTROLLED CIRCULAR CYLINDER FOR NOTAR^{TM} TAIL BOOM

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Abstract: Lift on circulation control (CC) circular cylinder is calculated via numerical simulations based on 2D realizable *k*-ε epsilon viscous model and compared with experimental data. The simulation result shows an acceptable agreement with tested data. With the proved grid and simulation method, series of simulations are conducted to study the effect of parameters on lift. Single slotted tail booms under different down wash velocities are optimized with the principle of generating maximum total moment around the main rotor shaft with same total power consumption. The results show that larger jet flow velocity, or smaller blow angle, or larger diameter of the cross section can help generating larger lift while enhancing the attachment of both the jet flow and down wash flow. Multiple slotted tail boom is better because it increases lift with same total slot width, and can increase lift by increasing total slot width without causing separation, also it helps generating high steady lift at a big rank of slot attack angles. To mount a guide vane (GV) at the exit of the slot, or shape the upper slot wall like a smooth-GV, or design the slot with an edge fillet is not recommended because it reduces the velocity of both the jet flow and the upstream of the attached downwash flow. Compared with other shapes of the slots, arcs-profiled slot performs better because of larger jet flow velocity and smaller blow angle. In order to generate the largest moment with same total power consumed by the entire NOTAR^{TM} system, total width of the slots and slot attack angle should be optimized according to velocity of down wash flow.

Key words: helicopter; aerodynamics; NOTAR^{TM}; circulation control

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Nomenclature

C_μ	Momentum coefficient, defined as $2(\rho_{jet}/\rho_\infty)(H_t/\Phi)(V_{jet}/V_\infty)^2$, assuming $\rho_{jet}/\rho_\infty=1$
H/mm	Minimum width of a slot, called width of the slot, shown in Fig. 3
H_t/mm	Total minimum width of all the slots
L/mm	Length of a slot along the longitude of the circulation control (CC) tail boom
R/mm	Radius of an edge fillet at the exit of slot, defined in Fig. 3
$V/(\mathrm{m\cdot s^{-1}})$	Velocity magnitude or average velocity magnitude
R_u/mm	Radius of the upper wall of an arcs-profiled slot
R_L/mm	Radius of the lower wall of an arcs-profiled slot, all set as 10 mm
T/mm	Thickness of the wall or local thickness of the wall near the slots, shown in Fig. 3
Φ/mm	Diameter of the cross section of CC circular tail boom
$\alpha/(^\circ)$	Average angle position of the slot(s) measured clock wised from the downwash velocity vector, shown in Fig. 3, called slot attack angle in this paper
$\theta/(^\circ)$	Angle between the walls of a wider inlet slot, shown in Fig. 3
$\beta/(^\circ)$	Angle between the first and last slots, shown in Fig. 3
$\gamma/(^\circ)$	Angle between the middle line of a slot and the tangency line of the outer wall at the exit of the

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slot, defined in Fig. 3, called blow angle

$\rho/(\mathrm{kg}\cdot\mathrm{m}^{-3})$ Density

Subscripts

jet	Property of a jet flow at the exit of a slot
∞	Property of down wash flow
inlet	Property of boundary condition set for the inner edge of the calculation field (Fig. 4)

INTRODUCTION

The concept of circulation control (CC) for high lift generation was developed in early 1960′s at the National Gas Turbine Establishment (U. K.) and has been investigated by a number of researchers since then. In a CC airfoil, a thin jet of air is blown from a span wise slot along a rounded trailing edge. This air jet remains attached over the curved surface because of the Coanda effect (the balance of centrifugal force and suction pressure). This results in an increase of the circulation around the airfoil and thus increases the lift on the airfoil[1].

The CC concept was applied to the NOTAR™ anti-torque system whereby the helicopter tail boom becomes a low-aspect ratio wing operating in a flow field generated by the main rotor (Figs. 1—2). The CC tail boom can be characterized as a conventional airfoil by lift (side force) and drag (download), as well as power required by the jet flows (Fig. 2)[2]. NOTAR™ anti-torque system does provide numerous and substantial benefits over the conventional systems in safety, reliability, maintainability, vibration and acoustics. But the power requirement issue holds backthis technology from fleet wide application. NOTAR™ anti-torque system must be optimized to deliver equal or improved performance over the conventional system with sizeable reduction in power requirement[2-6].

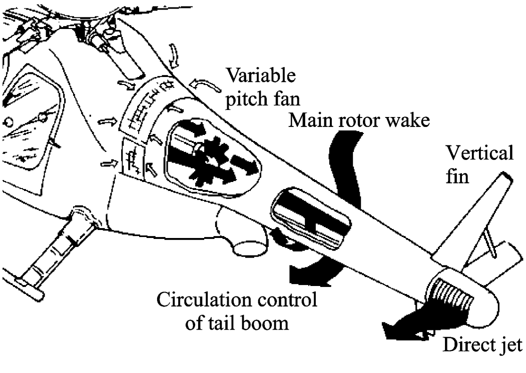


Fig. 1 Components of NOTAR™ system[4]

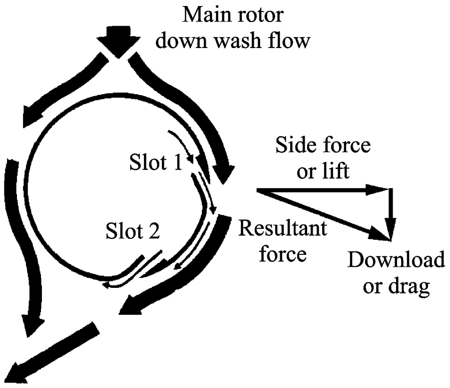


Fig. 2 Working principle of CC tail boom[5]

The NOTAR™ anti-torque system has already practically been used in MD520N and MD900 helicopters in America. But there is very few of public published researches on the effect of the related parameters on the lift. David T Fisher from the Naval Postgraduate School of the United States studied the effect of jet flow velocity, down wash velocity, and momentum coefficient (C_μ) on CC tail boom lift and drag by testing two different-cross-section tail boom in the NPS low speed wind tunnel in 1994[2]. Wang Huaming, et al from Nanjing University of Aeronautics & Astronautics (NUAA) and Luo Xiaoping, et al from First Aeronautical College of the Air Force of China studied the effect of the locations of the slots, C_μ, width of the slots, and the number of slots on pressure coefficient and side force coefficient by testing the tail boom both in two wind tunnels at NUAA and under rotating rotors in 1996[6-7]. Both the experimental studies summarized useful conclusions that could guide the optimization of a CC tail boom. Because of the lack of testing conditions in the few experimental researches and the limitation of the computer capacity around 1990s, the full vision of the geometry and testing parameters on the lift is still unrevealed.

The purpose of this paper is to study the effect of the parameters on lift, compare the potential of different shapes of slots and find a best performed slot shape, and optimize the construction of a CC tail boom in order that it generates the largest lift under the limitations of the geometry dimensions and power consumption. The studied geometry parameters is shown in Fig. 3.

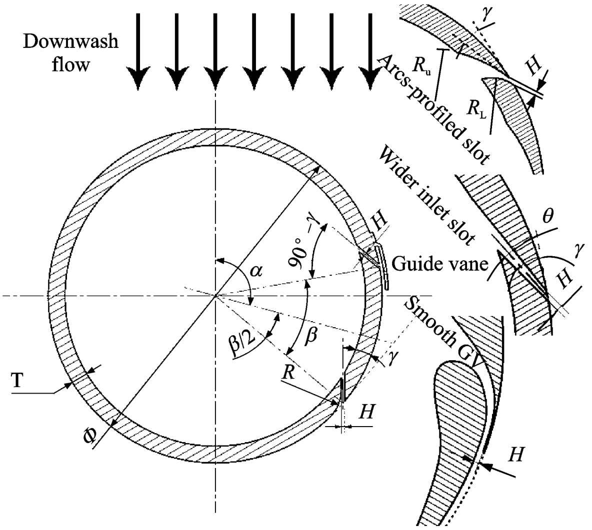


Fig. 3 Geometry parameters of CC tail boom

1 NUMERICAL APPROACH

1.1 Description of tested model

The model tested in Ref. [2] which is used for verifying the grids and computation method is a single slotted circular cylinder without a GV or an edge fillet at the exit of the slot. The geometry and testing parameters are shown in Tables 1—2 respectively. It is complicated to model the exact geometry of the slot because of its complexity and the lack of specific dimensions. The angle of γ is obtained by tens of sets of simulations.

Table 1 Geometry parameters of tested model

L/mm	Φ/mm	T/mm	H/mm	γ/(°)
508	114.3	6.4	1.0	51

Table 2 Testing parameters of tested model

C_μ	$V_{\text{jet}}/(\text{m}\cdot\text{s}^{-1})$	$V_\infty/(\text{m}\cdot\text{s}^{-1})$
0.3	72.1	18.0
0.4	77.5	16.7
0.5	82.5	16.0

1.2 Simulation grid

The validation simulation is performed on a 2D O-shaped grid with meshes both inside and outside of the CC tail boom. Allowing the interaction between meshes inside the CC tail boom and the outside environment to determine the flow inside the slot is a reasonable way to avoid over-specification of the boundary conditions at the slot exit nodes. Also the meshes inside the CC tail boom make it possible to consider the force caused by the inner pressure and the inner surface of the tail boom.

The calculation field is divided into five zones (A, B, C, D, E) with four concentric circles (Fig. 4). In order to get higher accuracy of results with less time consumed, the inner wall and the outer wall of the tail boom is meshed into 500 nodes respectively while outer boundary of calculation field is meshed into 200 nodes. Zones A, B, D are meshed with quadrilateral grids while zone C is meshed with triangular grids. The grid is shown in Fig. 5.

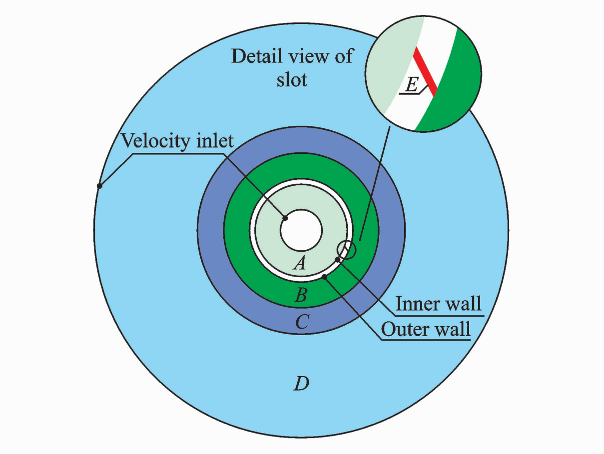


Fig. 4 Division of calculation field

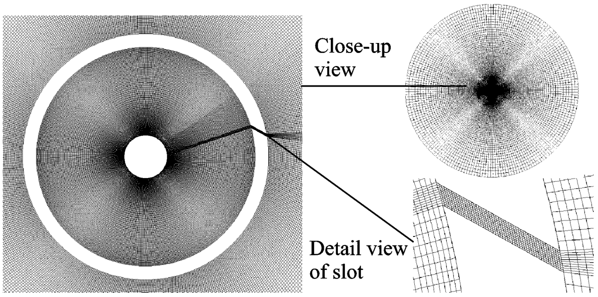


Fig. 5 Computational grid of tested model in Ref. [2]

The normal grid spacing between the outer surface and the first grid line is a crucial factor that affects accuracy of the result greatly. A bit larger or smaller of this spacing distance will make the side force either insensitive to the changes of the parameters or of no accuracy. The distance set in this paper is about 0.3 mm, which is about 0.002 59 times of Φ. For avoiding over specified boundary condition, the inner edge of calculation is placed far enough from the inner wall. The diameter of the inner edge is about 1/5 of the diameter of the inner wall. The outer edge of the calculation field is also set far away from the wall of the tail boom. The diameter of the calculation field is approximately 100 times the diameter of the outer wall.

1.3 Calculation method

The governing equations are the two-dimensional pressure based Navier-Strokes equations for steady, viscous, and uncompressible flows. Realizable k-ε viscous model with standard wall functions near-wall treatment is used. The pressure is discretized using body force method, while momentum, turbulent kinetic energy and turbulent dissipation rate are discretized using third order MUSCL method. The no-slip boundary condition is applied to the surfaces.

The jet flow at the exit of the slot is accomplished by applying a velocity inlet boundary condition V_{bc} to the inner edge of the calculation field with a direction normal to the boundary. The average velocity of the jet flow is adjusted by changing value of V_{bc}. The outer edge of the calculation field is applied velocity inlet condition to simulate the down wash flow.

1.4 Validation of simulation method

Fig. 6 shows the comparison of calculated result with tested result. It shows that the simulation result agrees well with the test data at slot attack angles around 100° to 118°. The trends of the lift calculated changes according to the change of the slot attack angle and the change of C_μ are the same as those of the lift tested. The simulation also predicts the slot angle at which the stall happens.

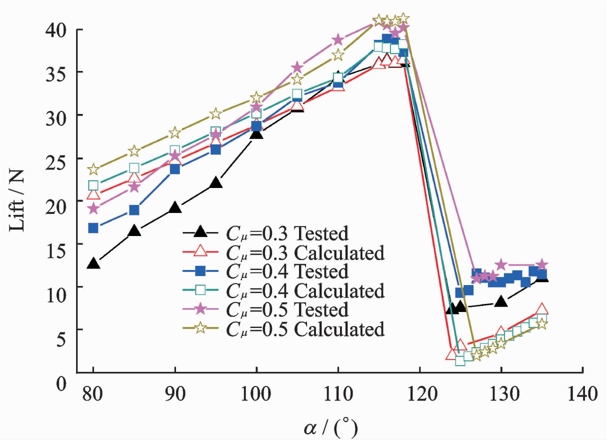


Fig. 6 Comparison between calculated lift and test data

In practical applications, the NOTAR™ tail boom is always mounted to the helicopter fuselage at a fixed slot attack angle which of course is a best performed angle. Take the tested model as an example, the model should be mounted to the fuselage at a slot attack angle of about 116°. The simulation result shows that 2D realizable k-epsilon viscous model is capable of finding out the best slot attack angles, distinguishing the effect of the parameters, and predicting the slot attack angles at which the stall occurres, which means that the simulation method is suitable for the parameter analysis of CC tail booms.

2 PARAMETER ANALYSIS PROCEDURES

The previous research has already suggested that lift is connected to geometry parameters including the shape of slots, width of one slot, number of slots, total width of slots, flow guide devices, and testing parameters such as slot attack angle, velocity of the jet flow and down wash flow. Although a lot of different models have been tested, the specific effect of some parameters on lift is still unrevealed because of the lack of comparison experimental research. However, to simulate every specific parameters of every slot shape with lot of dimensions in order to integrate the previous research is an unrealizable mission.

In order to complete the mission, the tested model with testing parameters, same as those when C_μ equals to 0.4 is used as a reference, and every parameter is simulated individually and compared with the reference. After the individual parameter simulations, some parameter combinations are conducted to verify the conclusions of the first simulations. The next job is to design the shapes of the slots with the guide of the simulation conclusions, research the effect of the parameters of the slot shapes, find out best performed geometry parameters of the best performed slot shape, and finally, try to construct a tail boom with the best performed slot in order that the tail boom generates the largest lift under the limitations of the geometry dimensions and power consumption.

3 RESULTS AND DISCUSSIONS

The results of the parameter analysis simulations are shown in Fig. 7. All the parameters except those specially pointed out are same as the referenced situation.

The effect of V_{jet} is mainly shown in Fig. 7(a) and also reflected in Figs. 7(i—k). With the purpose of comparing the effect of the different slots under approximately same power consumption, all V_{bc} is set as same as the referenced situation unless V_{jet} is specially given. Fig. 7(a) shows that larger V_{jet} is helpful to generating larger maximum lift and for the attachment of the flows. The results shown in Figs. 7(i—k) also prove this conclusion. If a slot of a same shape with a same blow angle performs better, it is mainly because of the larger jet flow velocity.

The effect of V_∞ can be found in Figs. 7(b,e, i—o). The results indicate that (1) For a specific model with a given V_{jet}, there exists a specific V_∞ which makes the tail boom generate the largest maximum lift; (2) For the slots with a same total width, a better performed slot always performs better under different V_∞; (3) As V_∞ increases (C_μ increases accordingly), maximum lift may also increase; (4) Larger V_∞ is harmful to the attachment of the flows. The second conclusion give us a reason to optimize the slots in order that the CC tail boom generates the largest maximum lift with approximately same power consumption under any down wash velocity. It is necessary to explain the sudden drop of lift of models marked with hollow stars in Figs. 7(p—r). The reason is not stall but that the stagnation point is out of the surface of the CC tail boom.

Figs. 7(a—b) explain the result of the experimental data (Fig. 6). The reason why lift of the experiment increases according to the increase of C_μ is that both the increase of V_{jet} and the decrease of V_∞ from 18 m/s to 16 m/s make the lift increase.

The result of local thickness near the slots is shown in Fig. 7(h). The function of T (actually the length of the slot in cross section plane) for the jet flow is similar to a barrel for a bullet. The simulations prove that a considerably large T helps to determine the direction of the jet flow and helps the jet flow to accelerate to its maximum velocity. Lift is not very sensitive to T when T is already considerably large (6.4 mm is already large enough for the simulation models with γ equal to 30°). The effect of diameter of CC tail boom is shown in Fig. 7(e). The result shows that larger Φ is helpful for generating larger lift and for the attachment of the jet flow.

Fig. 7(f) shows the effect of angle between the double slots for double slotted tail booms. The results show that double slotted tail booms are better than the single slotted ones in many aspects. A double slotted tail boom with a not too large β can not only increase the maximum lift (not always) but also maintain the high lift at a large range of slot attack angles (also proved in experimental study in Refs. [5, 8]). Actually multiple slotted is also helpful for the attachment of the flows for models with a same total slot width. The effect of slot width is shown in Fig. 7 (c,g). The results show that larger H is helpful for generating larger maximum lift, but too large slot width makes the jet flow act like a direct jet flow. Figs. 7(m,q,o) prove that to add more slot (s) is a considerable way of increasing lift and enhancing the attachment of the flows by increasing the total slot width while decreasing the width of each slot.

In practical applications, the compressed air is mostly consumed by the direct jet (Fig. 1). The pressure of the compressed air keeps approximately the same as the width of the slot changes, which means the velocity of the slot jet flow will keep approximately same according to the change of the total slot width. Thus V_{bc} is set according to the proportion of H_t. CC tail boom with larger total slot width of course consumes more power, but the NOTAR™ system may produce more moment with a same total power consumption. The following equation can be used as a criterion to examine whether gaining ΔF more lift with ΔH_t more total width generates more moment than the compressed air is consumed by the direct jet

$$\Delta F > 2X_d \cdot (V_{jet})^2 \cdot \rho_{jet} \cdot \Delta H_t \cdot (X_e - X_b)/(X_e + X_b)$$

where X_d, X_b and X_e are the distance from the main rotor shaft to the direct jet, the beginning slot and the end slot, respectively. It is assumed that the velocity of the slot jet flow equals to the velocity of the direct jet flow. Actually the tail boom is more efficient than the direct jet, usually the slot generates more moment around the main rotor shaft than the direct jet with the same compressed air consumption.

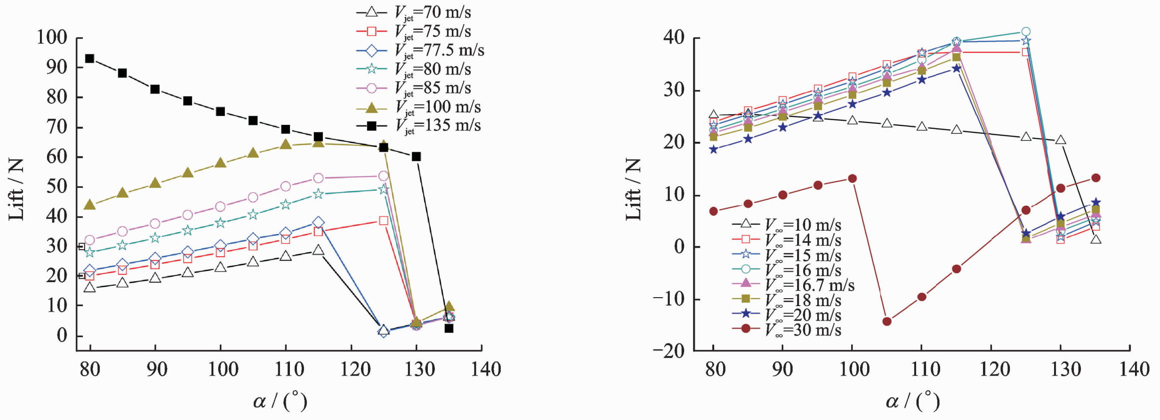
Figs. 7(d, g—k) show the full vision of the effect of γ. The results show that smaller γ is helpful for the attachment of the flows and for generating larger lift for all slot shapes under all down wash velocities. Because of the great effectiveness, to minimize the blow angle is a direction of designing the slots, and to mount a GV at the exit is one of the approaches.

Up to now, the simulations have already revealed most laws of increasing the lift. Among all the potential approaches, Φ is constrained by the size of the helicopter fuselage, V_∞ is a parameter which normally cannot be optimized due to the constraints of designing the rotor system and its rotation speed, and V_{jet} is limited not only by the power consumption but also the initial shortage of the air compressing system. The available approach left is to shape the slot(s) properly which generate(s) faster jet flow with minimized blow angle, and optimize(s) the total slot width in order that the NOTAR™ system generates the largest moment with same total power consumption.

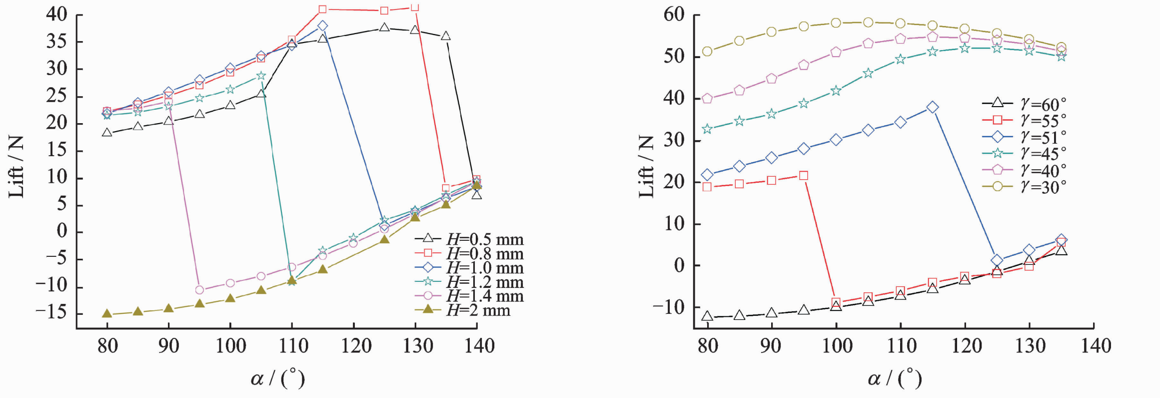
To set the width of the slot inlet larger may increase V_{jet}, to mount a GV at the exit of the slot can minimize the blow angle, and to profile the slot with arcs can lead to a wider inlet and a smaller blow angle. A smooth-GV is constructed by combining GV and the arcs-profiled slot, whose GV is not outside the circular cross section of the tail boom and the actual blow angle is also close to 0°. The shape of these four slots is shown in Fig. 3. The thickness of the GV or the smooth-GV equals to 0.3 mm and the minimum width between (smooth) GV and the tail boom surface equals to 1 mm.

The results of the effect of different shapes are shown in Figs. 7(i—k) respectively. It shows that to increase V_{jet} by setting the slot inlet wider is achieved because of the wider inlet slot, arcs-profiled slot and slot with a GV at the exit. Because of the geometry constraints, γ can not be set too small and θ can not be set too large for the wider inlet slot. While for arcs-profiled slot, R_u can be set large enough to make the inlet wider, and γ can be set as small as 5°. Thus arcs-profiled slot performs much better than the wider inlet slot does.

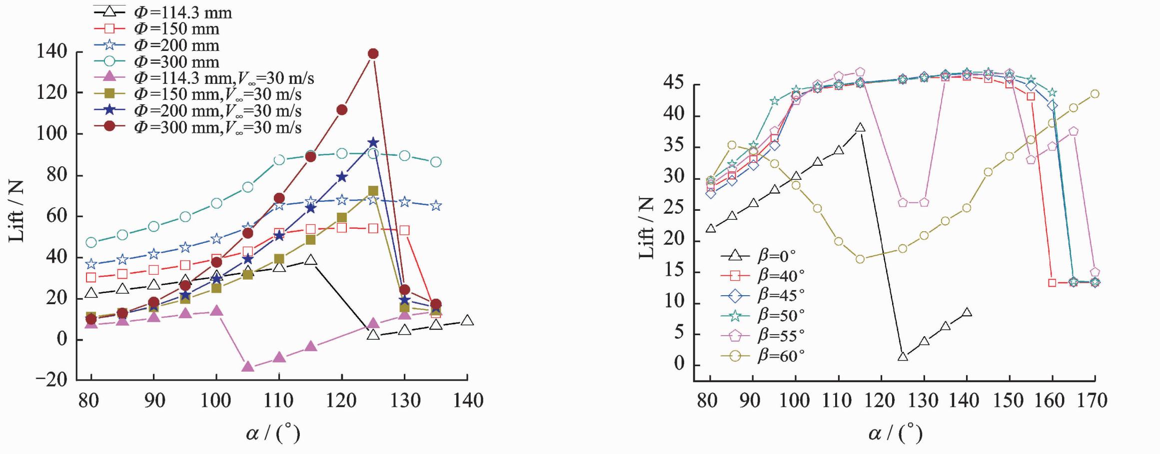
Because of the great importance of γ, it seems that slot with a GV or smooth-GV at the exit would perform better than the wider inlet slot or arcs-profiled slot would do. But the result of the simulations shows that neither GV nor smooth-GV is a better choice. The reason is not only that the (smooth) GV causes total pressure loss, but also that the (smooth) GV separates the jet flow from the attached down wash flow. The separation between the flows decreases the velocities of both the jet flow and the upstream of the attached down wash flow which directly decreases the circulation around the tail boom surface. This is also the reason why even with same V_{jet}, slot with a GV can not perform as well as common strait slots (Fig. 7(k)). But for different



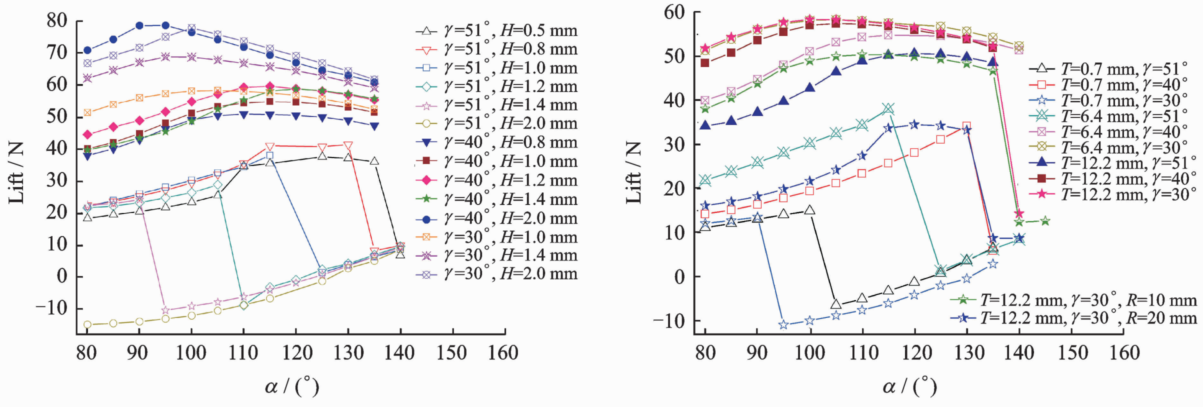
(a) V_{jet} (b) V_∞



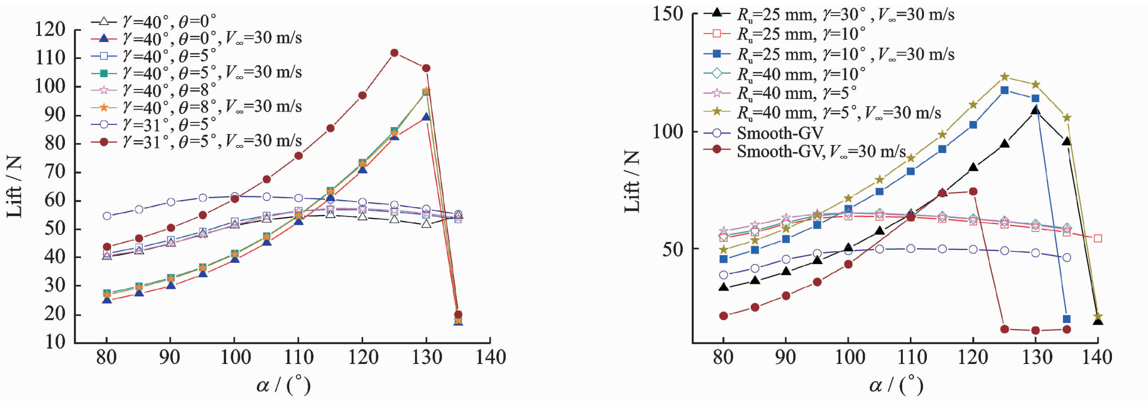
(c) H (d) γ



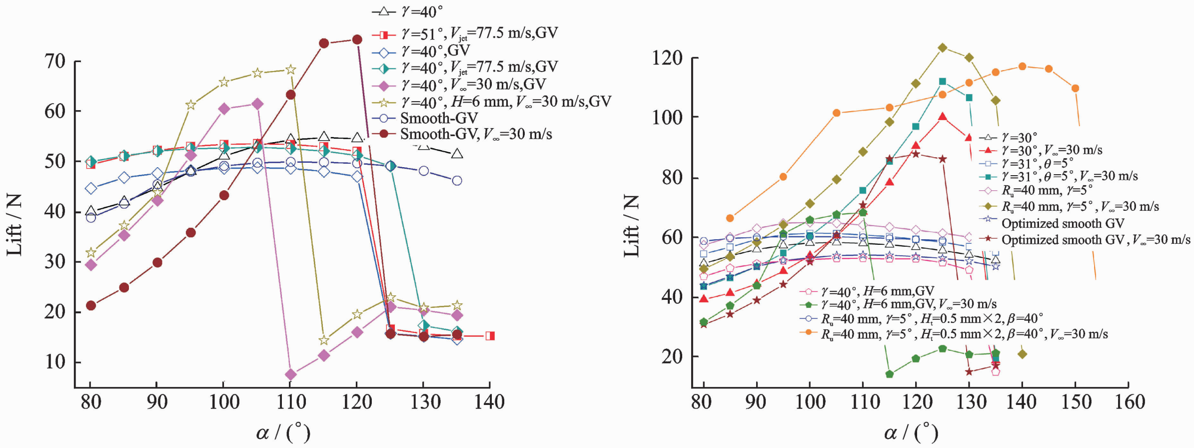
(e) Φ (f) β



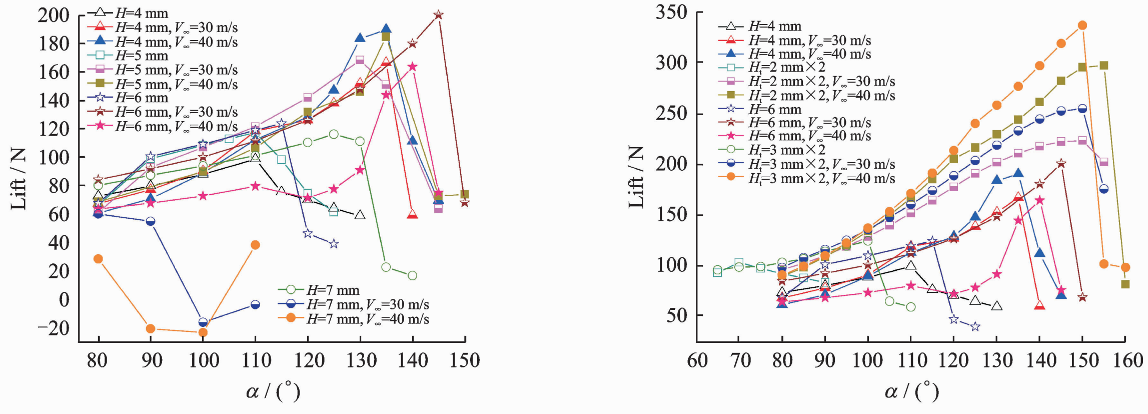
(g) γ and H (h) T, γ and R



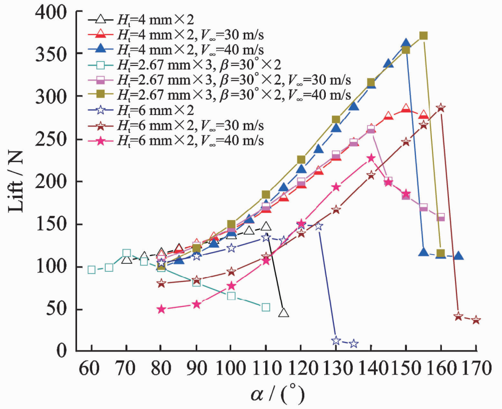
(i) α, α (wider inlet slot) and V_∞　　(j) R_u (arcs-profiled slot), γ, V_∞ and smooth GV



(k) γ, V_∞, GV and smooth GV　　(l) Comparison of best performed slots of different shapes



(m) H for arcs-profiled slots with R_u=40 mm and γ=5° under different downwash velocities　　(n) H and H_t for arcs-profiled slots with R_u=40 mm and γ=5° under different downwash velocities



(o) H_t for arcs-profiled multiple slotted tail boom with R_u=40 mm and γ=5° under different downwash velocities

Fig. 7　Lift on CC tail boom with effect of different geometries and testing parameters

γ with same GV, same V_{jet} results in same lift, the only difference is that the slot with smaller γ consumes less power. Compared with normal GV, smooth-GV slot generates larger lift because the smoother slot shape and smoother GV causes less loss of total pressure. The result also implied that GV or smooth-GV is only helpful for the attachment of the jet flow while not for the attachment of the down wash flow. The edge fillet at the exit acts similar to smooth-GV slot does. Although edge fillet causes no total pressure loss, the jet flow is slower and the jet flow is also separated from the attached down wash flow. The effect of edge fillet at the exit is shown in Fig. 7(h).

The comparison of the best performed slots of each kind is shown in Fig. 7(l). The result indicates that single arcs-profiled slotted tail boom generates the largest maximum lift. Slots with (smooth) GV perform the worst. Smooth-GV slot is optimized by making the slot similar to the arcs-profiled slot and making the GV shorter. Although optimized smooth-GV slot performs better, it is still not a good choice because of the separation of the flows. Fig. 7(l) also implies that tail boom with single arcs-profiled slot generate the largest lift under down wash velocities of both 16.7 m/s and 30 m/s consuming approximately the same power with the referenced tested model.

As discussed above, slots with larger total width have the potential to produce more moment with whole NOTAR$^{\text{TM}}$ system consuming the same power. Since total power consumption is also related to the longitude positioning of the slot (s) and the direct jet, the following discussion only focuses on that total slot width may produce largest the maximum lift without considering the power consumption. The best performed slot shape with best performed geometry parameters is chosen to optimize the (total) slot width. The results of tail boom with different (total) slot width are shown in Figs. 7(m—o). The results indicate that the best (total) slot width is different under different down wash velocities. The optimized slot width for single slotted tail boom is close to 6, 6 and 4 mm under downwash velocities of 16.7, 30 and 40 m/s. Multiple slots with the same total slot width greatly increase the maximum lift, and it is believed that by reassigning the slot width and intervals between the slots, the tail boom may perform better.

It is clear that lift is related to almost all the geometry and testing parameters listed above among which α, β, γ, R and the slot shape are not related to C_μ, which means different models with the same C_μ or same model with the same C_μ at different slot attack angles can result in different lifts.

4 CONCLUSIONS

(1) Smaller blow angle, or larger velocity of jet flow, or larger diameter of the cross section of the CC tail boom, or double slots rather than single slot are helpful for generating higher lift.

(2) Smaller blow angle, or larger velocity of the jet flow, or smaller slot width, or smaller velocity of the downwash flow, or larger diameter of cross section of the CC tail boom, or double slots rather than single slot is helpful for the attachment of the downwash flow and the jet flow. GV or smooth-GV is helpful for the attachment of the jet flow but harmful for the down wash attached flow because of the separation caused by the (smooth) GV.

(3) Width of slot, total width of slots, and slot attack angle are the parameters that should be optimized according to the velocity of down wash flow in order that the tail boom generates the largest lift with the same total power consumed by the whole NOTART$^{\text{TM}}$ system.

(4) Multiple slotted tail boom performs much better because it not only increases maximum lift with a same total slot width, but also increases total slot width without causing the separation of the attached flows which increases maximum lift even further. Also, compared to single slotted tail boom, multiple slotted tail boom can maintain high lift at a much larger rank of slot attack angles.

(5) It is not recommended to have an edge

fillet at the exit of the slot because it slows down the velocity of the jet flow and thus reduces the lift.

(6) GV and smooth-GV decrease the maximum lift because they slow down the velocities of both the jet flow and the upstream of the attached downwash flow.

(7) Arcs-profiled slot performs the best because it increases the velocity of the flows while minimize the blow angle.

(8) Although lift is not very sensitive to angle between the slots and the local thickness of the wall near the slots, the local thickness should be large enough to accelerate the jet flow and determine the direction of the jet flow, and the angle between the slots should not be too large otherwise the rank of high lift slot attack angles would be narrowed.

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