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DEVELOPMENT OF HALF-MODEL TEST CAPABILITY AT THE NF-3 WIND TUNNEL

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Abstract

Half-Model test has important meaning in the research of aerodynamic performance, high-lift system and flow control techniques of transport and civil aircraft. Half model experiments are implemented at 3.5m by 2.5m low speed wind tunnel of NF-3 in Northwestern polytechnical University (NPU) on a civil aircraft configuration with high lift devices and nacelle and a calibration wing-body half-model. The aerodynamic influence of the spacer, which located between the fuselage and the wind tunnel wall, is investigated on two half-models with different size using different spacer heights which are proposed in different literatures. According to the comparison between the half-span and full-span experiment results and the flow visualization results around the fuselage, the height of spacer should be decided by the size of the fuselage rather than the parameters of boundary layer of wind tunnel wall as proposed in some literatures, and when the height is close to the boundary layer thickness, the results show obviously abnormal. The aerodynamic influence of the joint structure of high-lift system is studied, and the results show that the joint structure between the slats and the main wing may induce separation and affect the stall performance dramatically, especially the joint structure close to the fuselage.

1 Introduction

Since the start of half-span techniques in 1990's at Airbus wind tunnels, the half-model test techniques has become a useful testing capability in many wind tunnels, especially in the research of high-lift devices. The half-span testing techniques has been suggested as a tool that should be developed to provide state-of-the-art wind tunnel research capabilities[1].

Due to the sensitivity of high lift configurations to Reynolds number, performance characteristics obtained at low Reynolds numbers may result in a non-optimal result at high Reynolds numbers. As a result, it becomes meaningful to increase the Reynolds number even to flight Reynolds number in high-lift devices experiments[2]. Half-span model test can increase the Reynolds number effectively because of the increasing the model size. Besides increasing the Reynolds number, the half-model has several advantages such as an advancement in simulation of model, a reduction on cost of model, and so on. But it has an inherent short comings because of the influence of the wind tunnel wall boundary layer on the aerodynamic performance of half-model by modifying the freestream approaching the model close to the wall and reducing the model's effective aspect ratio. The influence mechanism of wall boundary layer on half-model and how to reduce this influence is a research focus and the key technique in in half-model testing till now.

The mostly used approach to reduce the influence is using a spacer(or in other words, a stand-off or a peniche) between the fuselage and the wind tunnel wall or wall suction[3]. Due to the effects of the presence of the spacer on the aerodynamic characteristics (so called "spacer effect"), a optimal spacer height is vital technique in using a spacer. Some activities on the influence of the height and shape of a spacer have been reported. According to the reported literatures, different explanations of the spacer effect have been reported as follows: (1) In

ELIRET project[4], the researchers analyse the numerical results and experimental results in ETW and find that the main peniche effect on the model flow is based on its additional flow displacement leading to an additional flow velocity around the fuselage and the inboard wing compared to a configuration without a peniche. The strength of the peniche displacement effect is directly linked to the angle of attack of the configuration by means of a lift rise with increasing peniche height growing with increasing angle of attack. (2) In EUROLIFT program[5], the free-flight calculation results are compared with experimental and numerical in-tunnel results and the spacer effect is explained as that the mounting of the half model in the tunnel causes a redistribution of the velocity field due to cross flow velocity components in the plane of symmetry of the half model. (3) Some researchers explain the spacer effect as that the presence of spacer changes the effective diameter of fuselage and increases the up-wash effect of the fuselage, which compensates the reduction of lift coefficient in half-model test[6]. (4) In JAXA/CTT project[7], the researchers analyses the variation of the induced drag evaluated by the relation between CD and square of CL, and find two remarkable features: the first one is that drag coefficient at zero-lift angle of attack which is estimated by the extrapolation is observed almost the same among each of the spacers, and the other is that the slope of the curve becomes lower when the spacer height increases. Therefore, it can be said that the effect of the spacer installation is mainly caused by a change in effective aspect ratio. According to their explanations, different optimal heights based on different parameters have been proposed, such as a quarter to half of the local wall boundary layer thickness, or two (or two to three) times of dispalcement thickness of local wall boundary layer, or one-sixth to one-third of fuselage diameter. Till now, due the lack of a persuasive explanation of spacer effect, there is no a general standard for the optimal height of spacer in half-model testing.

From the previous analysis, the optimal height of spacer can be related to two patterns: the parameters of wall boundary layer or parameters of model size. The optimization criteria is also two patterns: comparing the half-model experimental results with the full-model experimental or CFD results. Three questions exist in these optimization criteria. Firstly, the experimental results of full-model are needed and the experimental and CFD results both show that the half- and full-model results cannot agree well. Secondly, different optimal results and influence mechanism of wall boundary layer are proposed from different experiments. Thirdly, the conclusions are from a certain experiment using a fixed size model in a certain wind tunnel test section that will lead to a lack of persuasiveness in the conclusions.

In present paper, at first, an effect of the height of the spacer on aerodynamic coefficients and flows around the fuselage and inboard of wind are presented using experimental results of two half-models with different size. Each model has several spacer heights based on different parameters, such as the thickness and displacement thickness of wall boundary layer, the fuselage diameter, etc. Based on the aerodynamic coefficient and flow visualization results, a suggestion of the optimal spacer height for half-model testing is proposed. Finally, the influence of the joint structure of high-lift system on the aerodynamic performance of half-model is investigated.

2 Facility and Experimental Apparatus

2.1 NF-3 Wind Tunnel

NF-3 low speed wind tunnel in NPU is an atmospheric pressure straight flow wind tunnel with three test sections: two-dimensional (3m by 1.6m), three-dimensional (3.5m by 2.5m) and propeller test section. The present experiments are conducted in the three-dimensional section.

The half-model experiment is conducted in the three-dimensional test section with the model mounted vertically on floor with a turntable to change the angle-of-attack, as shown in Fig. 1.

2.2 Half-Model Balance

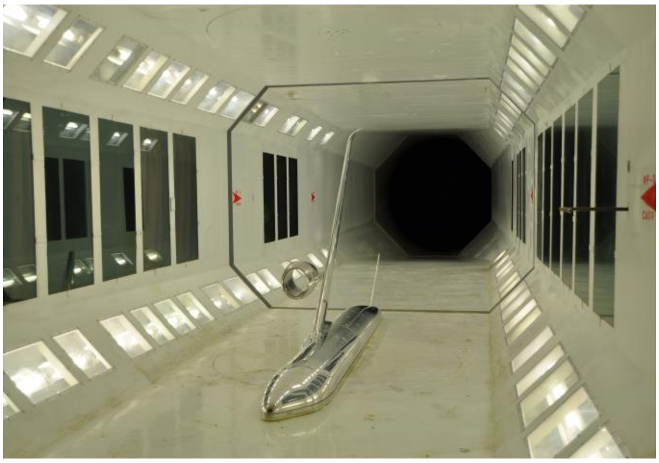


Fig. 1 Half-model installed in NF-3 test section

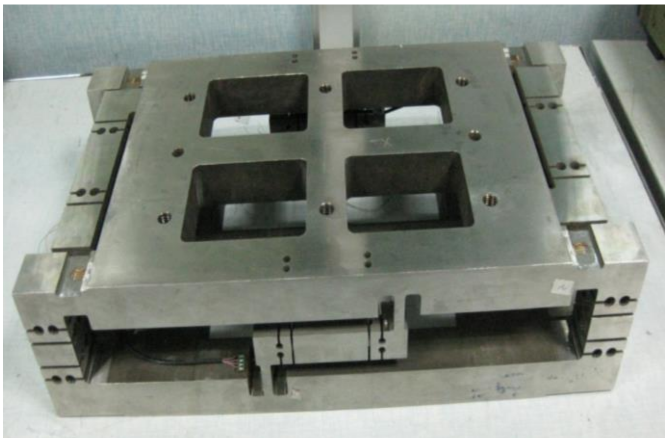


Fig. 2 BMTP2 half-model balance

Due to the aerodynamic characteristics of half-model test, special force balance is needed. There are two types of half-model balance: internal and external balance, which is internally and externally mounted to the wind tunnel model during the testing process[8-10]. Typically referred to half-model test, three- or five-component externally balance is mostly used. According to the mounting requirement in NF-3 wind tunnel, a new half-model force balance BMTP2 for half-model test is designed. BMTP2 is a six-component box type balance, mounted internally in the model. The structure sketch of BMTP2 is shown in Fig. 2, and capability parameters are shown in Table 1.

Table 1 BMTP2 half-model balance capabilities(N, N▪m)

	Y	X	Z	M_Y	M_X	M_Z
Design load	6000	5000	1500	2000	1000	2800
Error（%）	0.24	0.06	0.29	0.04	0.12	0.12

3 Experimental Model and Installation

3.1 Civil aircraft Half-Model

The experiment is implemented using a generic high-lift configuration of civil aircraft model with a nacelle(Fig.1). The relative angles of leading-edge slats and trailing-edge flaps are changed by changing the joint between the slats/flaps and main wing. A replaceable spacer is mounted between the fuselage and the floor of wind tunnel. In present experiment, 7 kinds of height of spacer is tested. The heights are designed according to different parameters and they are 10mm(about the displacement thickness of boundary layer of wind tunnel wall, δ^*), 20mm(2 times of δ^*), 30mm(3 times of δ^*), 55mm(about one-fourth of the diameter of fuselage), 70mm(about the thickness of wall boundary layer), 80mm and 90mm(some researchers advised). The balance is installed in the fuselage and the spacer.

3.2 Calibration Half-Model

Using a single model in a certain wind tunnel test section to optimize the height of space will lead to a lack of persuasiveness in the optimal results. As a result, besides of the former model, another smaller but simpler half-model (Fig. 3)

Fig. 3 calibration half-model

is tested in the same test section of NF-3 wind tunnel. There are 6 kinds of height of spacer and they are 10mm(about δ*), 20mm(two times of δ*), 30mm(three times of δ*), 45mm(about one-third of height of fuselage), 80mm (some researchers advised) and 110mm.

3.3 Installation and Labyrinth Seal Structure

In the present experiment, the half-model is installed vertically on the turntable of wind tunnel. The space is located between the model and floor to reduce the spacer effects. The balance is mounted in the fuselage internally to connect the model and the floor while out of contact the spacer. The installation sketch is shown in Fig. 4.

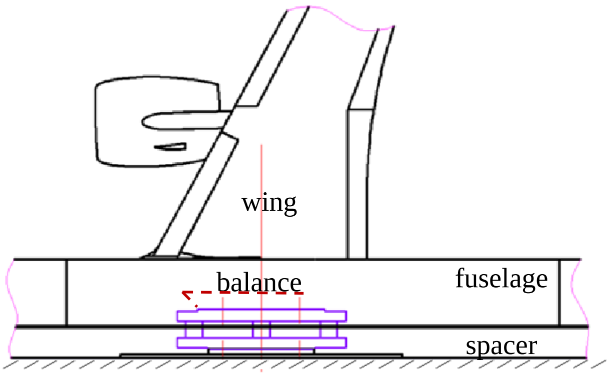


Fig4. Installation sketch of half-model

Theoretically, a completely airtight seal is desirable aerodynamically between the spacer and the fuselage while there must be no-contact. As a result, a labyrinth seal is used[11]. The fuselage side of the labyrinth seal is fabricated directly as an integral part of the flat side of the fuselage. In order to change the height of the spacer while keeping the labyrinth seal at every height, the spacer is divided into two parts: a labyrinth seal part with fixed and minimum height(10mm) , and a height-changable part. A sketch illustrating the install location between the fuselage, the spacer, the balance and the wall, and the labyrinth seal is presented in Fig. 5.

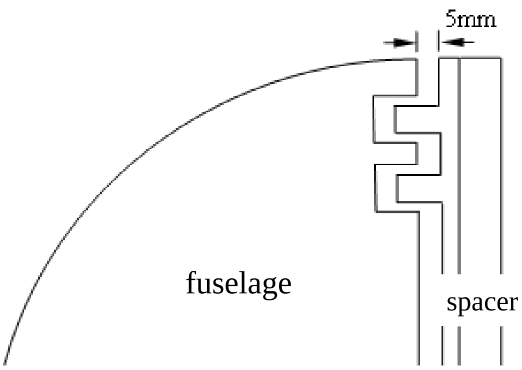


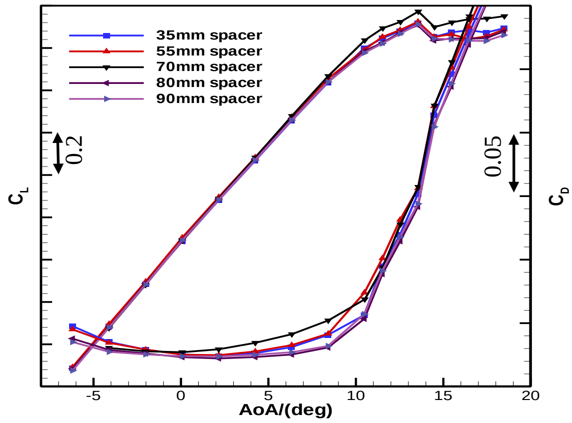
Fig.5 Sketch of labyrinth seal

4 Experimental Results

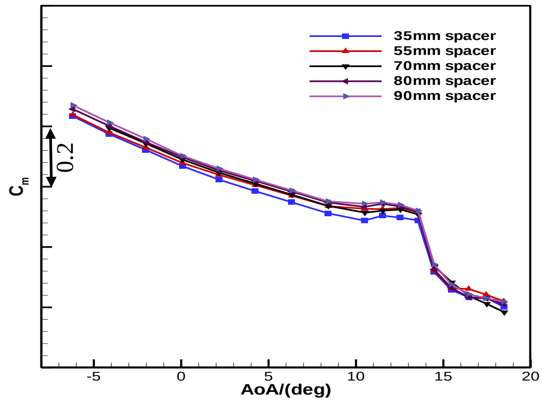
4.1 Spacer Effects on Aerodynamic Forces

In this section, the comparisons of basic aerodynamics between each of the spacer heights are shown. All data are provided after the corrections including blockage effect correction, lift effect correction and the correction of the tunnel wall.

Fig.6 gives the comparisons in lift, drag and pitching-moment coefficients with changing heights of the spacer at freestream velocity of 58m/s and cruise configuration. In order to simplify the figure, the heights of 10mm and



a. CL-α , CD-α



b. Cm-α

Fig.6 Spacer effects on lift and drag coefficient(with horizontal tail)

20mm are not shown. As shown in Fig.6(a), the influence of spacer height on CL is relatively small. As the spacer height becomes higher, the stall angle keeps almost the same and the slope changes slightly. Fig.6(b) shows that the pitching-moment reduces and the aerodynamic center moves as the spacer height becomes higher.

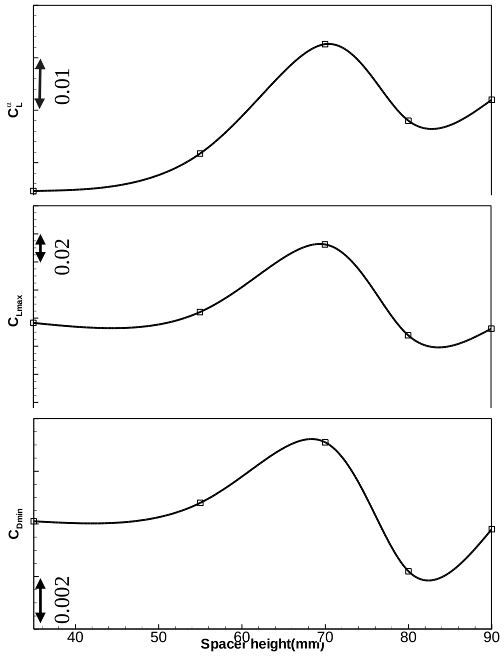


Fig.7 Spacer effects on characteristic parameters(with horizontal tail)

Fig.7 gives the characteristic parameter variation with the spacer height. Contrast to the conclusion of Yokokawa et al., where the slope of lift coefficient increases monotonically with increasing the spacer height, the slope increases but has a maximum value at 70mm. At this height, the CD_{min} and CL_{max} also have the maximum values. In order to determine that is caused by installation of flow patterns, the model is re-installed twice more, and the results agree very well that indicates a change in flow physics on the model roughly. The same situation appears when the horizontal tail is taken off, as shown in Fig. 8.

Fig. 9 gives the comparisons the flow patterns on the model for 20mm and 90mm spacer cases at AoA= 12deg and cruise configuration. At first, Fig.9(a) and (b) shows the flow patterns around the nose of model and the horseshoe

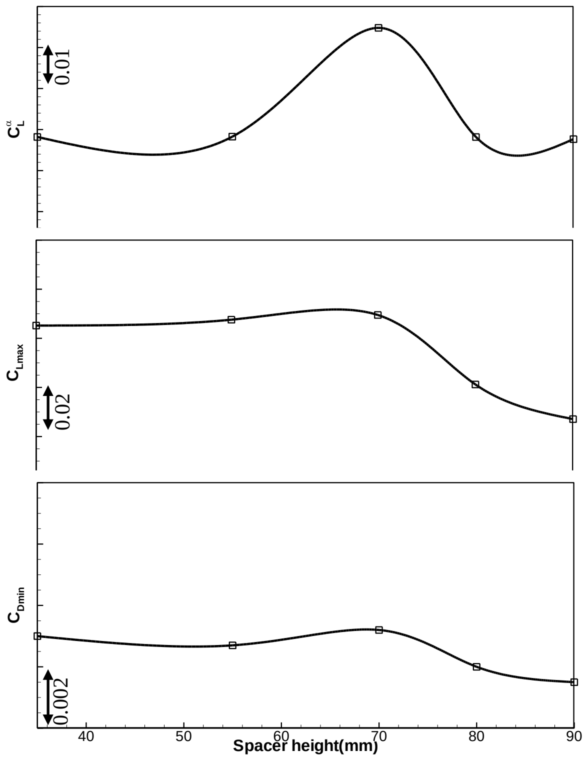
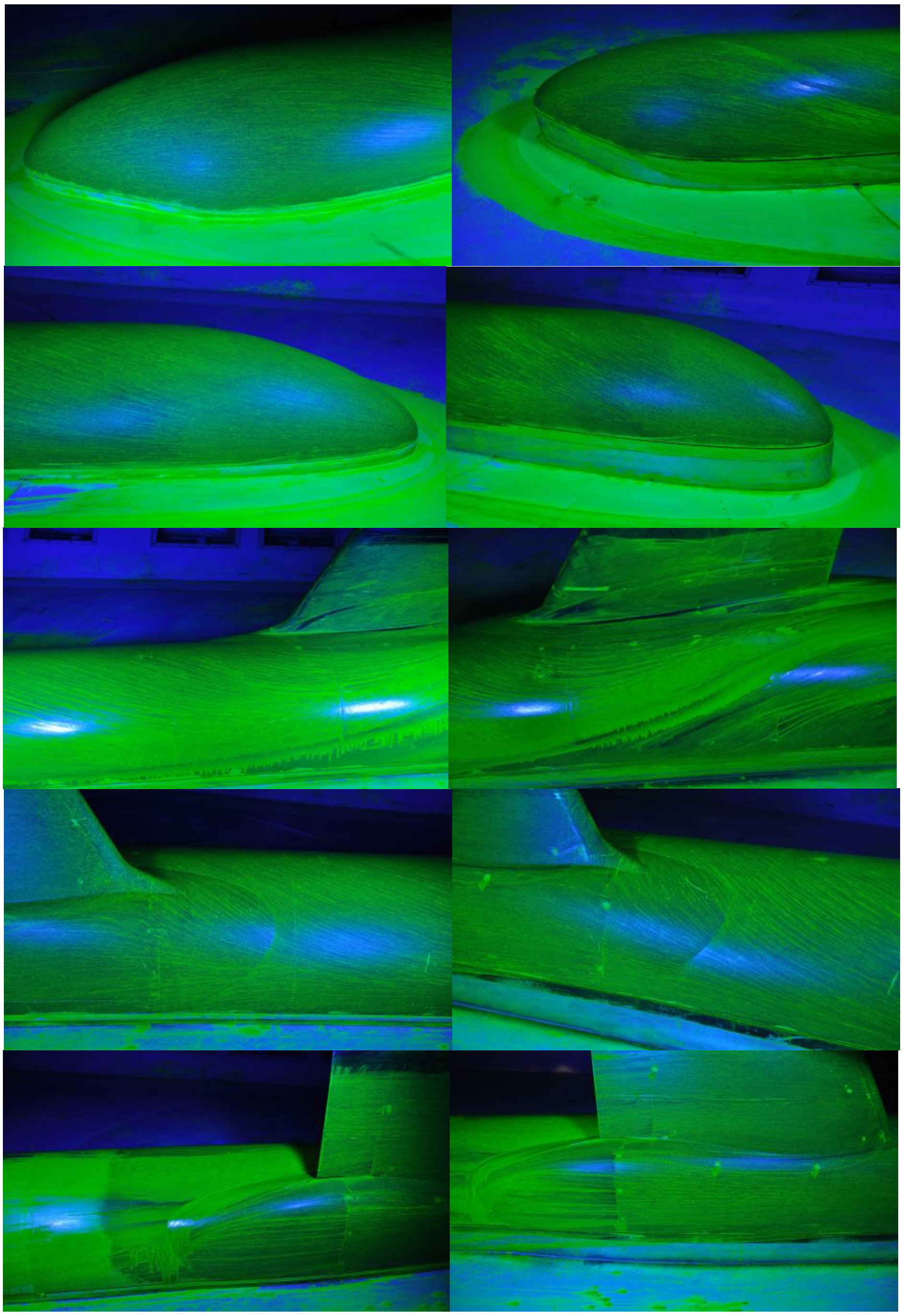


Fig.8 Spacer effects on characteristic parameters(without horizontal tail)

vortex formed by the boundary layer on a wind tunnel wall interacts with the fuselage. As the spacer becomes higher, the region of horseshoe vortex on wall becomes larger and the strength becomes larger. It also shows that the angle between the streamline on the model and the plane of symmetry of the half model becomes larger, that indicates that the flow on the symmetry plane is less symmetric at higher spacer. The results indicates that the flow on the symmetry plane in experiment is different from the CFD results using symmetric boundary condition. Secondly, Fig. 9(c) and (d) show the surface flow patterns around the leading edge of the wing-fuselage junction region. As the spacer becomes higher, the streamline around the leading edge becomes more curved. Fig.9(e) shows the surface flow patterns around the trailing edge and upper surface of the wing-fuselage junction region, and the results seem basically agree between two heights of the spacer cases. In the JAXA/CTT project, Yokokawa et al. investigated the flow patterns around the wing-fuselage junction region and the aft-fuselage and found that the local surface flow field around the fuselage and the inboard area of the wing was not largely affected by the variation of the spacer height. It seems that the experimental results in present paper do not support the conclusion proposed by Yokokawa et al.



(a)

(b)

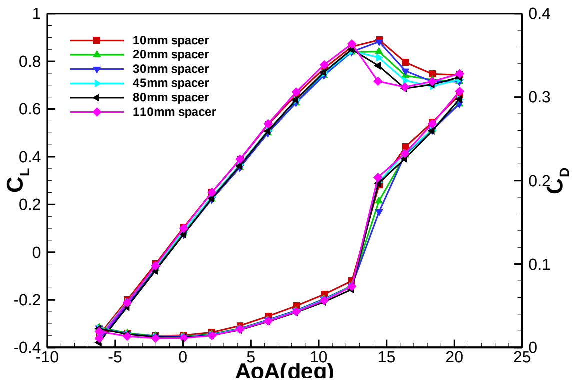
(c)

(d)

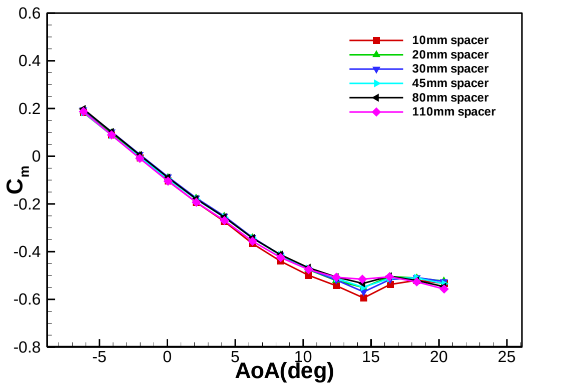
(e)

Fig. 9 Surface flow patterns around the fuselage region (AoA-12deg, left:20mm spacer; right: 90mm spacer)

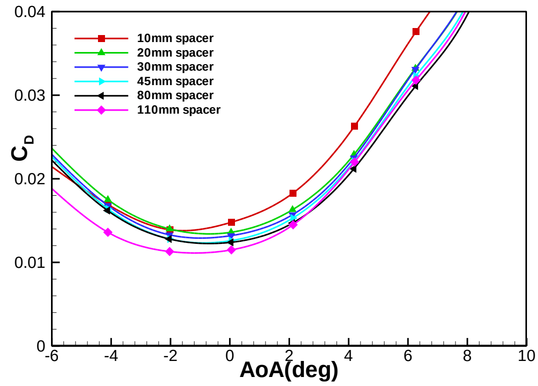
Fig. 10 gives the aerodynamic performance of the calibration half-model with smaller size for different spacer heights at freestream velocity of 58m/s. Obviously, the spacer influences the smaller model much more than the larger model. From the lift coefficient, the slope and stall angle change as the spacer height becomes higher. The slope shows the same trend as the results of former model that it does not increase monotonically with increasing the spacer height and a minimum value appears at the spacer height of 20 to 30mm, as shown in Fig.11. And the flow patterns around the front fuselage in Fig. 12 shows that the flow appears more



(a) CL- α , CD- α



(b)Cm- α



(c) CD- α (Close-up)

Fig.10 Spacer effects on aerodynamic performance the calibration half-model

symmetric on the plane of symmetry at this height. The close-up of the drag coefficient about the minimum drag(Fig.10(c)) shows that the drag decreases with the increasing of spacer height, and the angle of minimum drag becomes higher.

It is difficult to decide the optimal height of spacer at the lack of convincing explanation of the spacer effects. For the civil aircraft experiment, the optimal height are decided

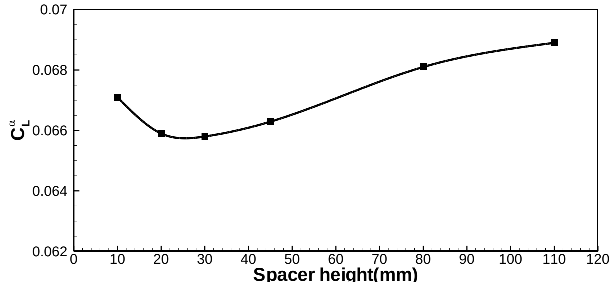


Fig.11 Spacer effects on characteristic parameters of the calibration half-model

Fig.12 Surface flow patterns around the nose region(Upper:20mm; Lower:110mm)

according to:(1) the slope of lift coefficient comparison between half- and full-model, (2)the angle of attack where Cm=0, and (3) the symmetry of flow in the plane of symmetry. As a result, H=55mm is selected. For the calibration half-model, the flow pattern in the plane of symmetry is observed at different heights and angles at the absence of full-model experimental results. The results show that the flow is more symmetric at the height of 20mm. The two optimal heights are about the 1/3 of the fuselage diameter respectively. According to above mentioned analysis, the optimal height should be determined by the size of the model rather than the thickness of wall boundary layer.

4.1 Spacer Effects on Aerodynamic Forces

In the CFD simulation of high-lift configuration, the slat tracks and flap track fairings are usually neglected to simplify the computational model. In the experimental model design, the flap track fairings are likely designed according to the reality while the shape and location of slat tracks are designed semi-empirically according to the structural strength rather than scaling. Besides the slat tracks, there also will be pressure measuring tube in the slot if there are static pressure probes on the slats.

In present experiment, the experimental results of half-model agree with full-model at cruise configuration. At high-lift configuration, two results agree well at the linear region of lift coefficient, while remarkable difference appears about the stall performance. The analysis shows that the slat joint structure and pressure tube effects the flow patterns and induce the flow separates earlier on the upper surface of main wing, especially the flow inboard area of the wing. In order to investigate the influence of the slat joint structure and pressure tube in leading edge slot, the model are modified to remove the pressure tube in slot and change the location of the slat joint structure inboard(as shown in Fig.13).

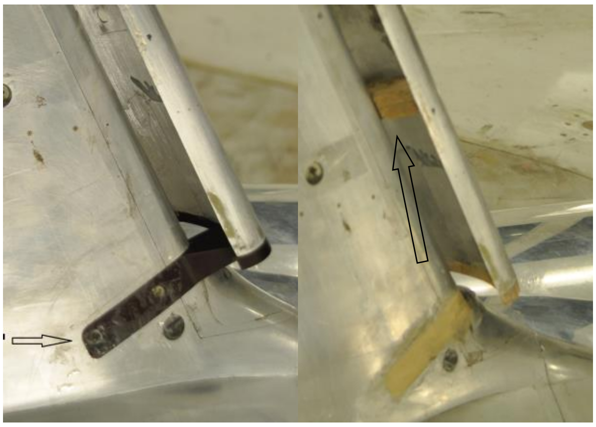


Fig.13 modification of joint structure inboard(left: before; right: after)

Fig. 14 and 15 show the effects of the pressure tubes and the joint structure inboard in the leading edge slot on the aerodynamic

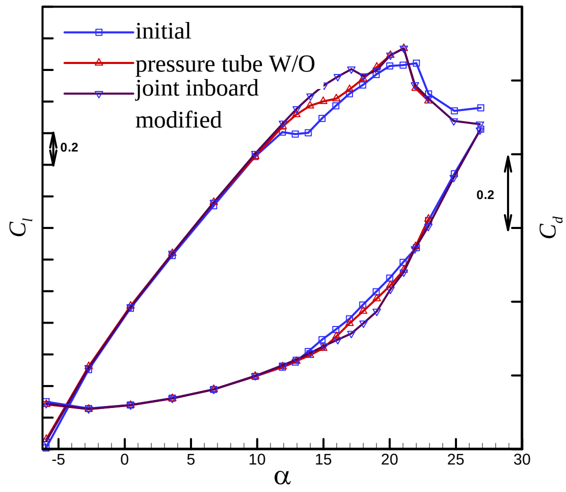


Fig. 14 Effects of pressure tube and joint inboard in leading edge slot on lift and drag

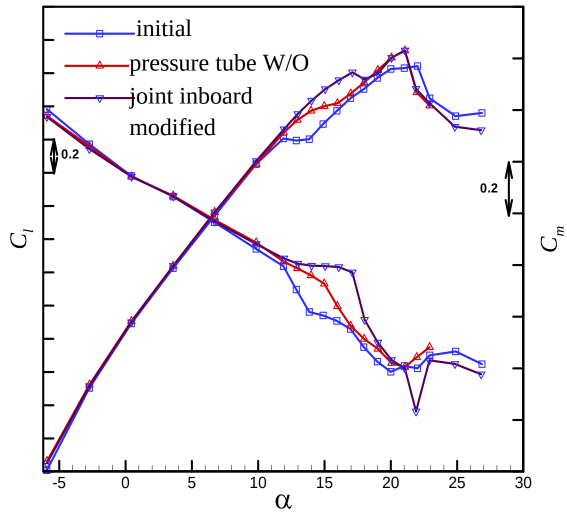


Fig. 15 Effects of pressure tube and joint inboard in leading edge slot on lift and moment

performance at landing configuration. The results show that in the initial state, the lift coefficient becomes nonlinear after 12 deg, and again increases linearly after 15deg until 22deg. At AoA of 12 to 15deg, the drag coefficient increases rapidly, and an added node down moment is shown in the moment coefficient. If the pressure tubes are moved away, the lift coefficient increases but the lift and moment coefficient remain nonlinear after 12deg. Furthermore, if the joint inboard is modified, the stall angle changes to 17deg and the slope of lift coefficient increases; the lift and moment coefficient become nonlinear still after 17deg. The results show that the pressure tubes and the joint structure inboard in the leading edge slot influence the flow patterns on the wing.

In order to understand the effects in detail, the flow patterns on the upper surface of wing are investigated. As shown in Fig. 16, region A and B are affected by the pressure tubes and the joint structure inboard in the leading edge slot respectively.

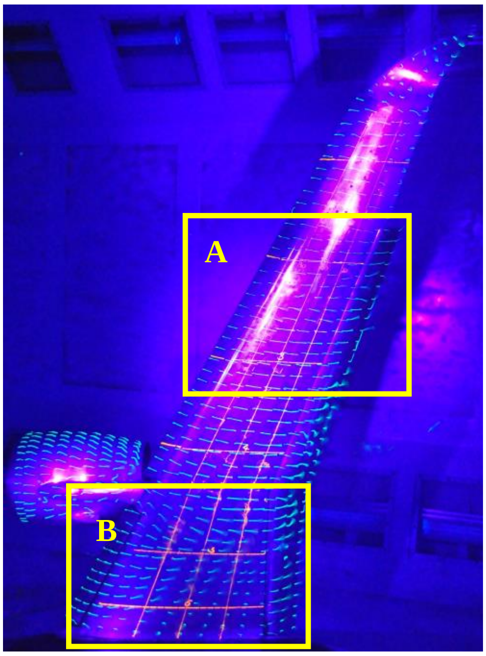


Fig. 16 comparison regions on upper surface of wing

Fig.17 gives the flow patterns on region A with/without the pressure tubes in leading edge slot at AoA of 13, 15, 17 and 19deg respectively. The flow patterns show that at the presence of pressure tubes, the flow becomes instable at 13deg, and separates at 15~17deg, and separates on the whole surface of main wing even the slat at 19deg. While, if the pressure tubes are moved, the flow remains attachment even to 19deg. It shows that the presence of pressure tubes in leading edge slot will lead to separation on large region and lose of lift force, and the angle of flow separation agrees with the angle of nonlinearity of lift and moment coefficient.

Fig. 18 gives the flow patterns on region B before/after the modification of the joint structure inboard in leading edge slot at AoA =11, 13 and 15deg respectively. The results show that before the modification, the flow becomes instable at AoA=11deg, and separates on a triangle area at AoA=13 and 15deg. After the modification, the flow remains attachment until AoA=15deg, and becomes instable slightly

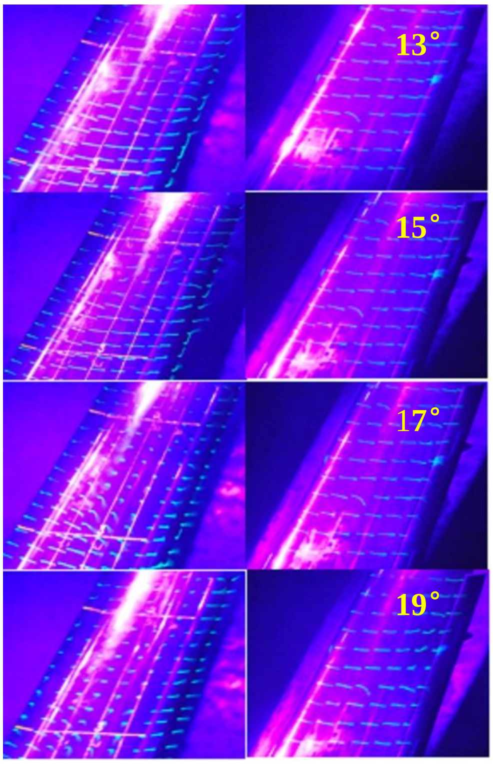


Fig.17 Effects of pressure tubes on flow patterns (Left: with; Right: W/O)

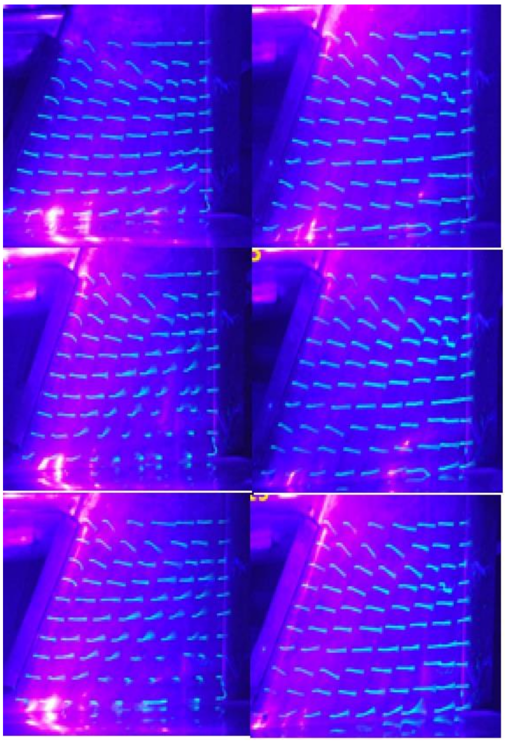


Fig.18 Effects of joint inboard on flow patterns (Left: before; Right: after)

at 15deg. The lift coefficient in Fig.15 shows nonlinear after 12deg severely even at the absence of pressure tubes; but once the joint structure inboard is moved outward, the lift coefficient increases linearly to 18deg. The flow patterns in Fig. 17 and 18 give the demonstration of the trends of lift coefficient mentioned above. Furthermore, the lift coefficient in Fig. 14 shows that a dump appears at AoA=18deg, and after that increases linearly further to 21deg. The dump shows that the flow separates on wing surface induced by the slat tracks in leading edge slot.

5 Conclusions

Half-model wind tunnel experimental techniques are developed in NF-3 low speed wind tunnel in NPU. A new half-model six-component balance is designed instrumented and calibrated to optimize the sensitivity and reduce the presence of interaction influences. Two half-models with different size are implemented to investigate the spacer effects.

Firstly, the variation of lift, drag and pitching-moment coefficient is observed when the spacer height is changed to different height proposed in literatures. Contrast to results in some literatures, the slope of lift coefficient is not increases with the height of spacer monotonically. CL_{max} and CD_{min} also have maximum values at the height of 70mm.

Secondly, the flow patterns around the nose and inboard of wing are observed. As the spacer becomes higher, the region of horseshoe vortex on wall becomes larger and the strength becomes larger. It also shows that the angle between the streamlime on the model and the plane of symmetry of the half model becomes larger, that indicates that the flow on the symmetry plane is less symmetric at higher spacer.

Thirdly, from the results of two model with different size, the optimal height should be determined according to the size of model rather than the thickness of wall boundary layer.

Lastly, the experimental results at high-lift configuration show that the slot tracks and pressure tubes in leading edge slot will induce the flow on main wing separate earlier and thus influence the stall characteristic strongly.

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