APPLICATION OF TRADITIONAL OIL-FLOW-VISUALIZATION TECHNIQUE IN DETERMINING SKIN-FRICTION FIELDS ON AXISYMMETRIC AFTERBODY MODEL

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Abstract

This study evaluated the application of the traditional oil-flow-visualization technique in determining skin-friction fields for surface flow of an axisymmetric afterbody model at low-speed conditions. Oil liquid, which was mixed of kerosene, titanium dioxide and oleic acid, was painted on the surface of model before experimental process. The movement of the oil was recorded by camera for data processing. The algorithm for extracting skin-friction fields was developed by the author and was validated. The method applied for boattail model. The results indicated that the traditional oil-flow-visualization technique provided sufficiently good outcomes for extracting skin-friction fields. Lagrange multiplier in range from 5 to 500 and number of selected pair images between 10 and 20 have a small effect on the skin-friction topology. The flow streamlines of the proposed method were also discussed detail in this study. Although the separation position was not captured well by the method, the reattachment position showed close results to previous observations. Consequently, the technique can be applied to analyze skin-friction fields of moving vehicles.

Keywords*: Skin-friction; oil-flow-visualization; SGLOF.*

1. Introduction

Skin friction is a very important parameter in aerodynamic studies. Although drag formed by skin friction is not high in comparison to pressure drag, the skin-friction topology allows understanding flow behavior close to the surface of model. In some case, the change of skin-friction fields leads to sudden change of pressure distribution, which affects drag of the model. A good pattern of skin-friction fields provides detailed understanding of aerodynamic phenomenon.

Previously, skin-friction fields were measured using oil flow visualization technique [1]. In this method, oil layer with white additives is painted on the black

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surface of the model before the wind tunnel test. A camera was then used to take picture on the surface after the wind tunnel test. From trace of oil layer, the skin-friction pattern could be discussed. In fact, the technique allows visualization with qualitative discussion. Since the experimental setup for method was simple, it is still applied widely for the aerospace industry for initial investigation.

To improve the oil film technique, luminescent oil is applied for the measurement. In this technique, oil medium is mixed with a small amount of luminescent dye. The oil is painted on the surface of model and is illuminated by UV LED during the experimental process. The change of oil layer thickness could be recorded for data processing. By comparison to the traditional technique, the luminescent oil shows high advantages such as faster responding time [2]. Consequently, some unsteady behavior of flow was discussed. However, the experimental setup for this measurement is sufficiently complicated, and luminescent dye is quietly expensive. Consequently, it has been not studied in Vietnam, yet.

In this study, we proposed to apply novel data processing for traditional oil-flow visualization techniques to study skin-friction fields. In detail, the experimental setup was the same as study of traditional technique. The change of oil layer is recorded during the experimental process by a digital camera. The sub-grid skin-friction measurement algorithm, which is developed by Tran and Chen [3], is applied for data processing. The results show that skin-friction fields can be captured well by the present method. Effect of Lagrange multipliers and the number of images on skin-friction topology are discussed in detailed in this study.

2. Sub-grid global luminescent oil-film (SGLOF) skin-friction measurement

The SGLOF skin-friction measurement developed by Tran and Chen [3] was now recalled for the current study. The technique was applied to solve the thin-oil film equation, which contains the relation between oil film thickness and skin-friction vectors. The change of oil-film thickness was considered proposal to the brightness of image, which could be recorded by the camera during experimental process. The equation showing the relation between the intensity of the image and skin-friction vectors is as follow:

$$\frac{\partial I}{\partial t}+\nabla \bullet\left(I\left(\frac{\kappa I}{2\mu}\boldsymbol{\tau}-\left(\nabla p-\rho g\ \right)\frac{\kappa^2 I^2}{3\mu} \right) \right)=0 \tag{1}$$

where $\boldsymbol{\tau}$ is skin friction vector, *p* is pressure distribution on the surface, *h* is thickness of oil layer, g is gravity and μ is the dynamic viscosity of the oil, $\kappa = h/I$ is a constant parameter, which shows relation between thickness of oil h and intensity I.

Previously, Tran and Chen [2] proposed applying filter on whole Eq. (1) to remain local feature of flow. This method is similar to the case of large eddy simulation (LES), which was widely applied in numerical study. When filter was applied, Eq. (2) becomes:

$$\frac{\partial \bar{I}}{\partial t} + \nabla \bullet (\bar{\boldsymbol{u}}\bar{I}) + \nabla \bullet \boldsymbol{\tau}_s = 0 \tag{2}$$

where $\bar{I}$ and $\bar{\boldsymbol{u}} = \frac{\kappa I}{2\mu}\bar{\boldsymbol{\tau}} - (\nabla p - \rho g)\frac{\kappa^2 I^2}{3\mu}$ are the luminescent intensity, optical-flow velocity fields in pixel grid and $\boldsymbol{\tau}_s$ is the sub-grid scalar flux. That parameter is determined by $\boldsymbol{\tau}_s = D_t \nabla I$, where D_t is the turbulent diffusion coefficient.

Eq. (2) was solved by Euler-Lagrange method. In this study, a Lagrange multiplier is applied. Since this study focuses on location of separation and reattachment flow, we used smoothness term as $J_R = \int_{\Omega} \alpha \left\| \nabla \bullet \bar{\boldsymbol{u}}(x,t) \right\|^2 dx$. Note that this relation is different from previous study by Tran and Chen (2020). One Lagrange multiplier was chose in this study. The optical-flow vecloticy vectors can be found by minimizing the below equations:

$$J(u) = \int_{\Omega} \left[\frac{\partial \bar{I}}{\partial t} + \bar{\boldsymbol{u}} \bullet \nabla \bar{I} + D_t \Delta \bar{I} \right]^2 dx_1 dx_2 + \int_{\Omega} \alpha \left\| \nabla \bullet \bar{\boldsymbol{u}}(x,t) \right\|^2 dx_1 dx_2 \tag{3}$$

where α is the Lagrange multiplier and is selected before numerical methods. Effect of Lagrange multiplier on solution will be evaluated in this study. Euler-Lagrange equation for Eq. (3) is:

$$\begin{aligned} \bar{I}_x \left(\bar{I}_t + \bar{u}\bar{I}_x + \bar{v}\bar{I}_y + D_t \Delta \bar{I} \right) &= \alpha \left(\bar{u}_{xx} + \bar{v}_{xy} \right) \\ \bar{I}_y \left(\bar{I}_t + \bar{u}\bar{I}_x + \bar{v}\bar{I}_y + D_t \Delta \bar{I} \right) &= \alpha \left(\bar{u}_{xy} + \bar{v}_{yy} \right) \end{aligned} \tag{4}$$

A discrete method to solve Eq. (4) was presented by Tran and Chen [3]. This method allows recovering of instantaneous skin-friction fields from a pair image, which is called a snapshot solution. By averaged snapshot solutions at different time, the mean skin-friction fields can be obtained. The experiment and results for validation of the method were presented by Tran and Chen in the previous study [2].

3. Experimental and numerical setups

Experimental setup for skin-friction measurement was presented in Fig. 1. Here, model is painted in black and is illustrated by the white light source, which is placed on the top surface. Model is painted by oil which is mixed of kerosene, titanium dioxide, and oleic acid by proposal of kerosene : titanium dioxide = 3:1 by mass and kerosene : oleic acid = 20:1 by volume. The change of oil layer was recorded by the camera at a frame rate of 5 frame per second (fps). The initial and final images are illustrated in Fig. 1.

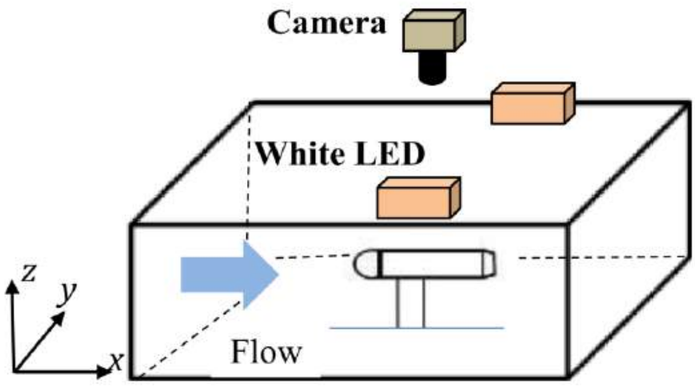


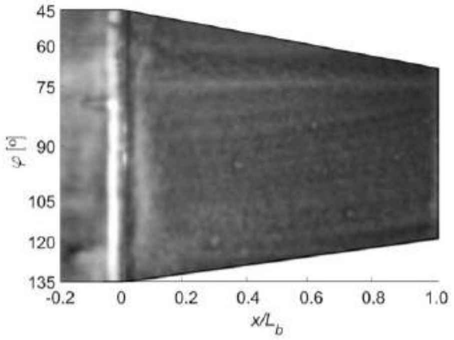
Fig. 1. Experimental setup for skin-friction measurement

The numerical region for boattail studies was shown in Fig. 2, time step between image is 1 s. A total of 15 image pairs is selected for data processing.

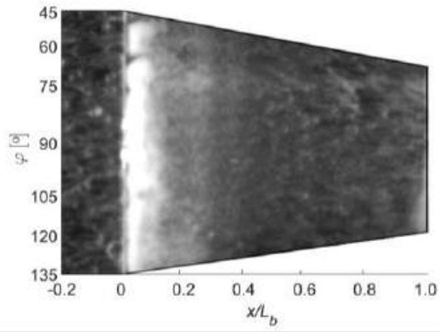
4. Results and discussions

4.1. Skin-friction on the surface

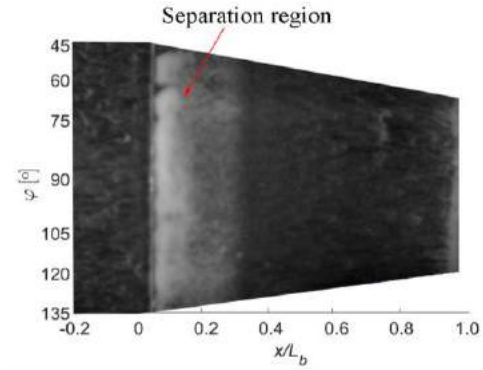
The first, processing and last images (before, during and after wind tunnel test) are indicated in Fig. 2. As can be seen clearly, the distribution of oil film is uniform on the surface. The movement of oil can be captured well by the camera. After the wind tunnel test, a high accumulation oil occurs near the shoulder of boattail. It is expected that separation occurs there. Tran et al. [4], who used luminescent oil film image to study skin-friction fields, indicated that the separation line occurs at the shoulder of boattail. Additionally, if the thickness of the initial luminescent is high, numerical results show that separation position moves downstream. Clearly, the selection of oil thickness is very important to obtain high accuracy of the results.



a) The first image (before wind tunnel test)



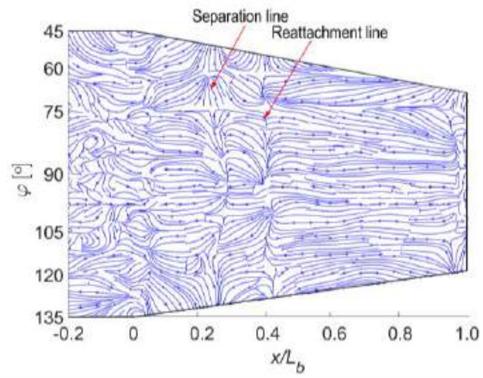
b) The image during wind tunnel test



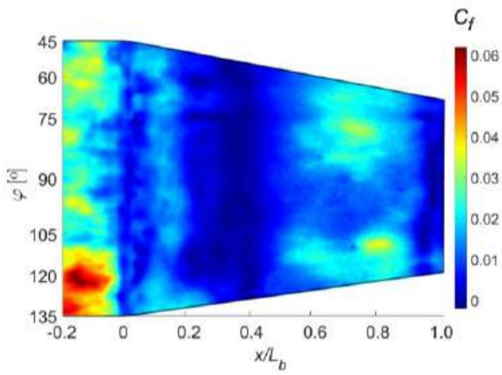
c) The last image after wind tunnel test

Fig. 2. The first, during and last images taken in experiments

We now show the numerical results, which were process by SGLOF algorithm. Fig. 3 illustrated the results of skin-friction lines and skin-friction magnitude. Here, 15 image pairs were used for data processing.



a) Skin-friction lines



b) Skin-friction magnitude

Fig. 3. Skin-friction lines and skin-friction magnitude

A clear skin-friction field was observed. In fact, flow is separated on the boattail surface and reattached again to form a separation bubble. The existence of separation bubble was widely reported in previous studies by Tran et al. [4] using experiments and Tran et al. [5] using numerical methods. However, it seems that the location of the separation position was not consistent well with the previous experimental study, where separation position is located near the boattail shoulder. In detail, when the thickness of oil is sufficiently thin, separation position should be located at the shoulder of the model [4]. In current study, separation position is located at x/L_b = 0.15. The difference is sufficiently large. It can explained by the movement of oil layer is affected by titanium dioxide in adverse pressure gradient region. Clearly, location of separation position is difficult to find.

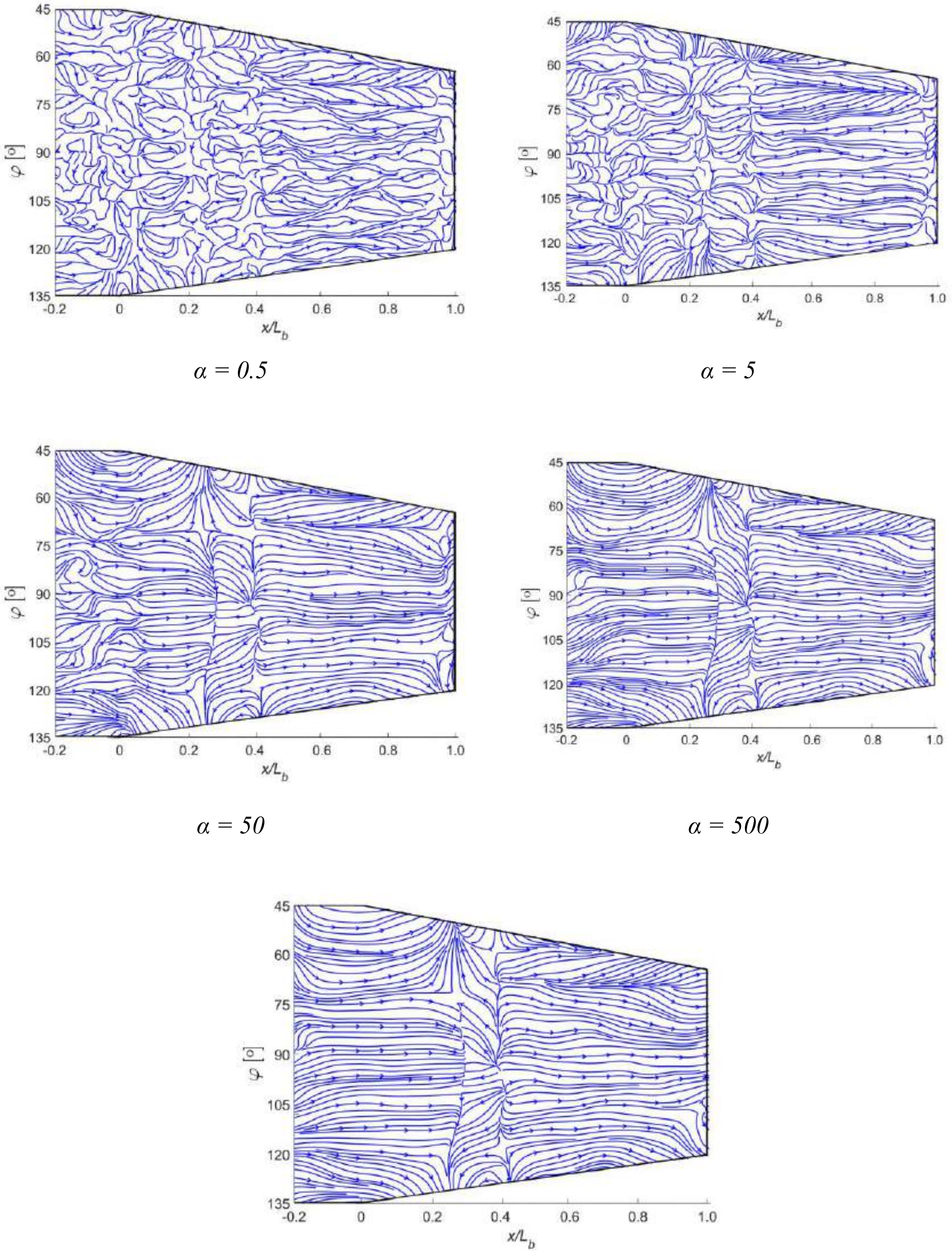
It can be explained that the oil layer contains solids components of titanium dioxide, which leads to a low respond to the aerodynamic effect. Additionally, the kerosene is evaporated during the experimental process, which may have some effect on the movement of the oil layer. Except for those points, clear flow streamlines was shown. High skin-friction value is also observed around the shoulder, where the velocity outside the boundary layer highly accelerates.

4.2. Effect of Lagrange multiplier on surface flow

Since an additional Lagrange multiplier is added to find skin-friction fields, the results of skin-friction are not unique. The solutions depend on the Lagrange multiplier α. In this section, the effect of weight coefficients on the numerical results will be discussed. We select Lagrange multipliers from 0.5 to 5000. Total 15 image pairs are employed for the evaluation. Results of the numerical process were indicated in Fig. 4.

Clearly, when the Lagrange multiplier was small, flow on the surface is not smooth and the pattern of skin-friction fields is not clear to observe. The flow fields become smooth for the Lagrange multiplier higher than 50. However, selection of too high multipliers leads to smooth flow and local features were not well captured.

Our results are highly consistent with the previous observation by Woodiga [6] and Tran and Chen [3], where flow fields were not affected by the Lagrange multiplier in the range from 5 to 500.



α = 0.5

α = 5

α = 50

α = 500

α = 5000

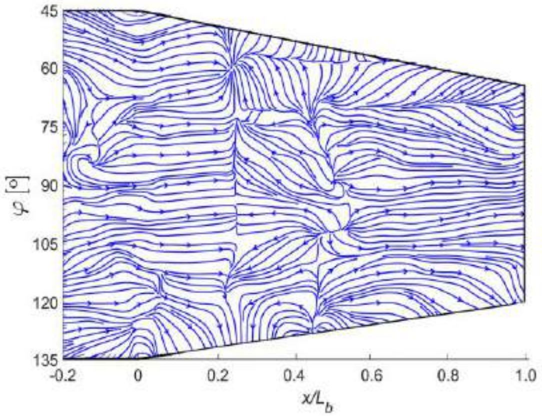
Fig. 4. Skin-friction lines for different Lagrange multiples.

4.3. Effect of number of image pairs on surface flow

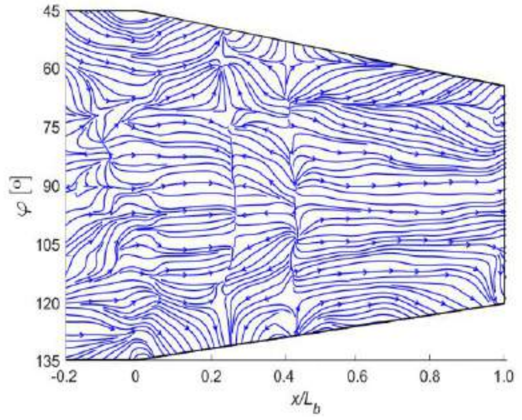
In this study, kerosene oil was used for experiments. However, the oil quickly evaporates during the experimental process. Consequently, selecting number of image pair is very important to obtain the correct results. The image number should be selected when the liquid substance is still sufficient for smooth movement. If the oil does not move, the uncertainty of skin-friction fields should be high. We examine the ability of the algorithm in extracting skin-friction fields by changing the number of image pairs for numerical process. Here, the initial image pair has remained the same for all cases. It means that the time increases with number of selected images. Fig. 5 shows the numerical results. Clearly, flow is not smooth for the number of pair images below 5. It is explained that in some areas, the oil does not succeed to respond to the flow movement and further image pairs are required for the results. However, when the number of the image is over 30 pairs, some part of the oil has finished movement. Processing for a pair image, which has almost no movement, will lead to large errors. Consequently, the number of selected image pairs is ranges from 10 to 20 is recommended for this study.

The advantage of the current skin-friction measurement method is to allow obtaining skin-friction values. Consequently, separation and reattachment positions can be evaluated quantitatively. Fig. 6 shows averaged streamwise skin-friction values at the centerline from different image pairs. Here, skin-friction was averaged on each point in a vertical position. The separation position can be determined by the skin-friction value cross the horizontal axis and becomes negative, while the reattachment position is determined by the position where skin-friction becomes positive. We can obtain a high resolution of skin-friction fields. Clear separation and reattachment positions were obtained. Overall, a low skin-friction region was observed near the shoulder, which showed the deceleration of flow there. After the reattachment region, skin-friction value increases, which indicates an increase of the pressure near the base. The results showed a similar trend to the previous study by Tran et al. (2018).

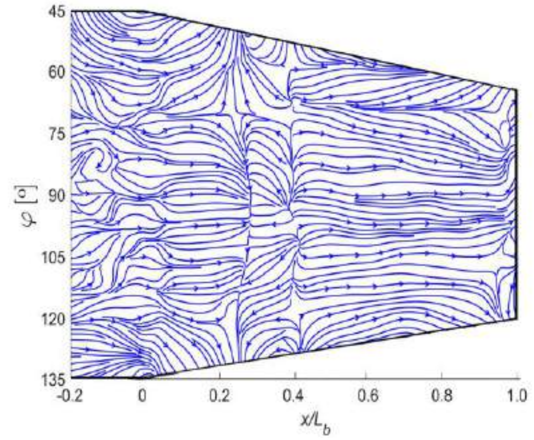
Fig. 7 shows separation and reattachment positions on the surface by the current and previous relevant studies [4, 5]. Clearly, the current technique shows a good ability in the prediction of reattachment position. However, the separation position is not able to capture well. Clearly, the selection of oil substance is very important to obtain high accurate results. It is an important topic for our further study.



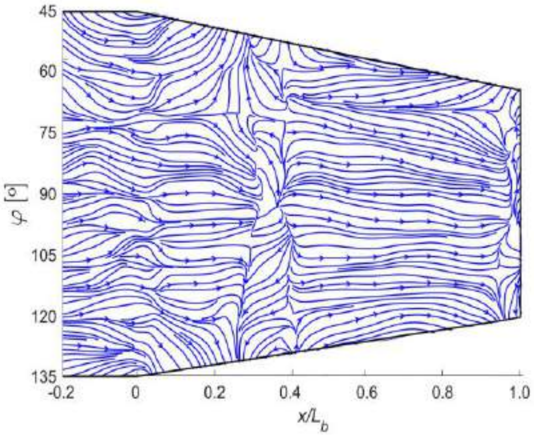
5 image pairs



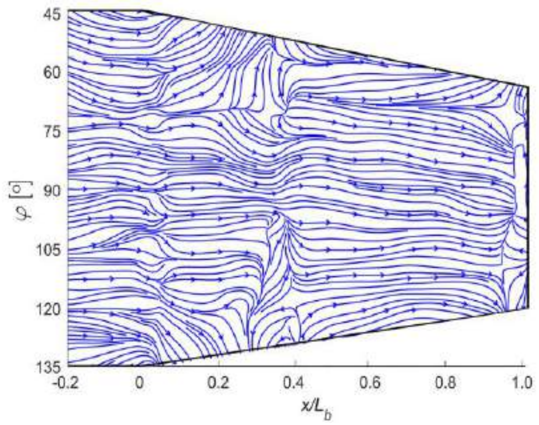
10 image pairs



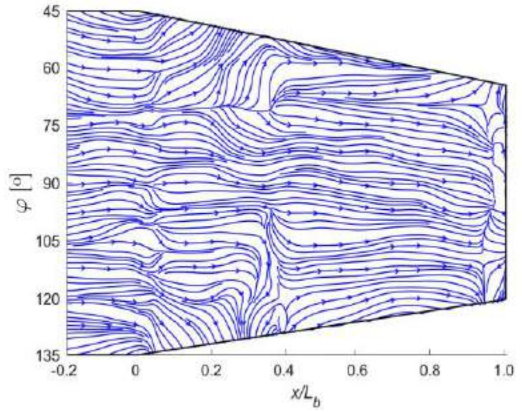
15 image pairs



20 image pairs



30 image pairs



40 image pairs

Fig. 5. Effect of image pair on the results

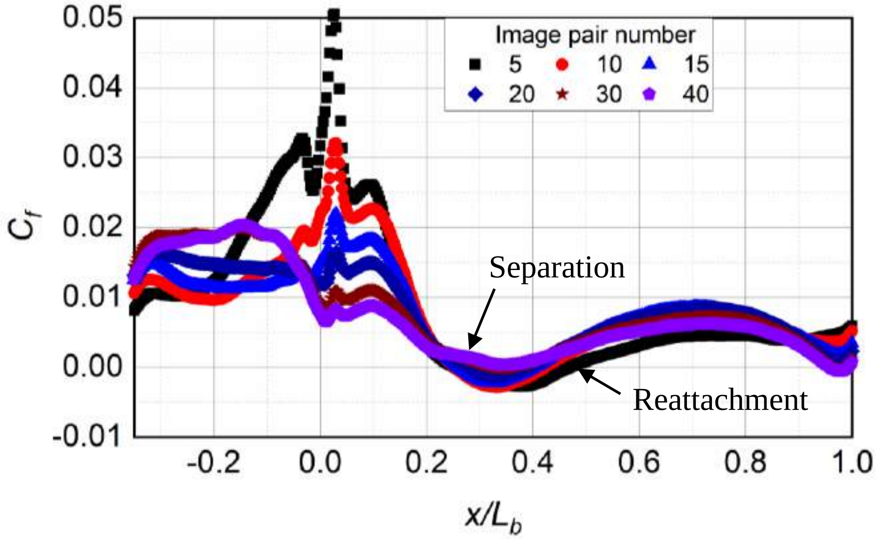


Fig. 6. Averaged skin-friction at centerline

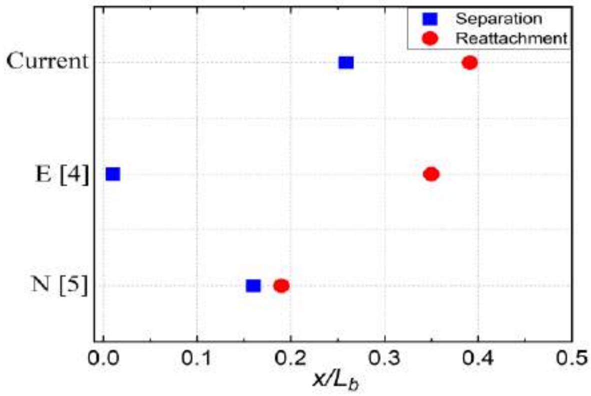


Fig. 7. Separation and reattachment position on the boattail surface
(N- is for numerical simulation and E- for experimental method)

5. Conclusions

In this study, a traditional oil-flow-visualization technique in determining skin-friction fields was evaluated. The skin friction was measured by oil-film and was processed by a sub-grid global luminescent oil-film skin-friction algorithm. The technique shows high potential in extracting skin-friction fields. Semi-quantitative skin friction was obtained with a clear structure of surface flow. The number of image pairs around 10 to 20 is good for capture skin-friction fields. Lagrange multiplier in the range from 5 to 500 practically does not affect the results. However, for further study, criteria for the selection of the Lagrange multiplier should be proposed for further development and unique results of the flow fields. Additionally, numerical results were affected by the movement of the oil layer and the number of image pairs. Consequently, the selection of mixing oil and number of image pairs should be carefully for further investigation.

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ỨNG DỤNG KỸ THUẬT HIỂN THỊ DÒNG CHẢY TRUYỀN THỐNG TRONG XÁC ĐỊNH TRƯỜNG MA SÁT TRÊN BỀ MẶT ĐUÔI VẬT ĐỐI XỨNG

Tóm tắt: *Nghiên cứu này đánh giá khả năng ứng dụng của kỹ thuật mô phỏng truyền thống trong xác định trường ma sát trên bề mặt của đuôi vật không đối xứng cho dòng vận tốc thấp. Dầu dùng mô phỏng là hỗn hợp của dầu hỏa, ôxit titan và axit oleic, được phủ lên bề mặt của mô hình trước thí nghiệm. Sự thay đổi của dầu được ghi lại bằng camera để xử lý. Thuật toán để tính toán trường ma sát đã được phát triển bởi các tác giả và được kiểm chứng. Phương pháp được áp dụng cho mô hình đuôi vát. Kết quả tính toán chỉ ra rằng phương pháp mô phỏng dầu truyền thống cho kết quả tốt trong xác định trường ma sát. Hệ số Lagrange được lựa chọn trong khoảng từ 5 tới 500 và số lượng cặp ảnh từ 10 tới 20 ảnh hưởng ít tới trường ma sát trung bình. Đường dòng quanh vật của phương pháp được trình bày cụ thể trong nghiên cứu này. Mặc dù vị trí tách dòng thu được không tốt từ phương pháp trên, vị trí hợp dòng khá tương đồng với kết quả của các nghiên cứu trước. Do vậy, kỹ thuật này có thể áp dụng để phân tích trường ma sát trên bề mặt của vật chuyển động.*

Từ khóa: Trường ma sát; hiển thị dòng chảy; SGLOF.

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