Joint Conference of APCATS, AJSAE & AAME 2023

October 11~14, 2023, JEJU Boo-Young Hotel & Resort, Jeju Island, Republic of Korea

Global Skin Friction Measurement and its Application in Aerospace Engineering

The Hung Tran[1,*] Quoc Tru Vu[1]

[1] Faculty of Aerospace Engineering, Le Quy Don Technical University, Hanoi, Vietnam

*Email: thehungmfti@gmail.com

Abstract

Skin-friction fields on the surface of flying objects are important for fluid dynamic researchers In this study, flow on slant surface. In this study, we present an optical-flow algorithm to determine the skin-friction fields on the surface of flying objects. The algorithm is based on solving the thin-oil film equation, which shows the relation between the thickness of oil layer and skin-friction vectors, with a sub-grid function. The thickness of oil layer is measured through the intensity of the oil-film coating on the surface. The change of intensity during the experimental process is recorded by a high-speed camera for data processing. The detailed descriptions of the experimental process, algorithm, and data processing are explained. Then, the current methods are applied for various types of flow in engineering applications, including flow around an axisymmetric boattail model, flow on a delta wing, flow on a low-aspect-ratio wing, and flow on the back of road vehicles. The application results show that the current technique shows a high ability in extracting flow on the surface

Keywords: Skin friction, thin oil film equation, optical flow, sub-grid algorithm

1. Introduction

Along with pressure, skin-friction fields on the surface of flying objects are important for fluid dynamic researchers. The skin-friction fields allow to explain the complex flow close to the surface, which shows more inside aerodynamic characteristics. This is important for the designing process, which helps reduce the separating region on the surface. Since the skin-friction vectors have tangent directions to the flow, measurement of the skin friction is a complicated task.

The previous measurement of skin friction is divided into local and global measurement techniques. Similar to other measurements, the global technique provides the values in the whole surface, which is highly advantageous in analyzing surface flow. The global measurement techniques include Shear-sensitive liquid crystal [1], surface-stress-sensitive film [2], and global-luminescent oil film [3], [4]. Among of them, the global-luminescent oil film, which is based on solving the thin oil film equation by an optical-flow algorithm, shows a simple and highly effective technique. The method was applied by many researchers [3], [5], [6].

This study provides some results of the global skin-friction technique, which was developed by Tran and Chen [4] in extracting skin-friction fields in some typical engineering applications. From the results, it confirms that the technique is able to use in further studies in analyzing the complex flow fields around the surface. The short summary of the technique is presented in Section 2.

*The Hung Tran

Section 3 shows the results and the conclusion of this paper is summarized in section 4.

2. The skin-friction measurement technique

The sub-grid global skin-friction measurement developed by Tran and Chen [4] was now recalled for the current study. The technique was applied to solve the thin-oil film equation, which includes the relation between oil film thickness and skin-friction vectors (Eq. 1). Here, the change of oil-film thickness was considered a proposal to the brightness of the image, which could be recorded by the camera during the experimental process. The thin oil film equation shows as [7]:

$$\frac{\partial h}{\partial t}+\nabla\cdot\left[\frac{h^2\boldsymbol{\tau}}{2\mu}-(\nabla p-\rho\boldsymbol{g})\frac{h^3}{3\mu}\right]=0 \quad (1)$$

where p is pressure distribution on the surface, h is the thickness of oil layer, g is gravity and μ is the dynamic viscosity of the oil. The thickness of oil film h is considered a proposal to the luminescent intensity I, i. e. $h = \kappa I$. The equation above changes to:

$$\frac{\partial I}{\partial t}+\nabla\cdot(I\boldsymbol{u})=0 \quad (2)$$

with $\boldsymbol{u}=\frac{\kappa I}{2\mu}\boldsymbol{\tau}-(\nabla p-\rho\boldsymbol{g})\frac{\kappa^2 I^2}{3\mu}$.

The thin-oil film equation was solved in previous studies by Liu and Shen (). The technique was successfully applied for flow on delta wing, wing-junction flow, and others, which showed high ability in extracting of skin-friction fields. However, since Gaussian filter was applied on the images, the flow becomes smooth. Consequently, some feature of flow was not preserved. To overcome that problem, Tran and Chen [4] proposed applying a filter on whole Eq. (1). The method allows to solve large features and to recover of small features by a sub-grid scalar function. This method is similar to the case of large eddy simulation (LES), which was widely applied in numerical studies.

The effect of gravity and pressure gradient is often small and can be neglected. However, in the region of high adverse pressure gradient, pressure could have some effect on skin-friction measurement. The uncertainty related to pressure gradient is often less than 2% and is neglected in this study.

Eq. (2) was solved by the Euler-Lagrange method with a smoothness constraint. A discrete method to solve Eq. (3) was presented by Tran and Chen [4]. This method allows for recovering instantaneous skin-friction fields from a pair image, which is called as a snapshot solution. By averaging snapshot solutions at different times, the mean skin-friction fields can be obtained. A typical setup of the skin friction measurement is shown in Fig. 1.

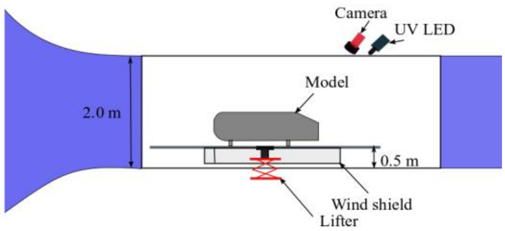


Fig. 1. The setup for the global skin-friction measurements

3. Results and discussions

3.1. The flow on an airfoil

Typical results of the skin-friction fields on a low-aspect-ratio wing surface are shown in Fig. 2. In this case, the angle of attack was set up at 18°. It is clear that the skin-friction fields are highly consistent with the oil-film pattern, which is captured for the camera. The most advantage of the measurement technique is that the skin-friction magnitude can be obtained from the measurement methods.

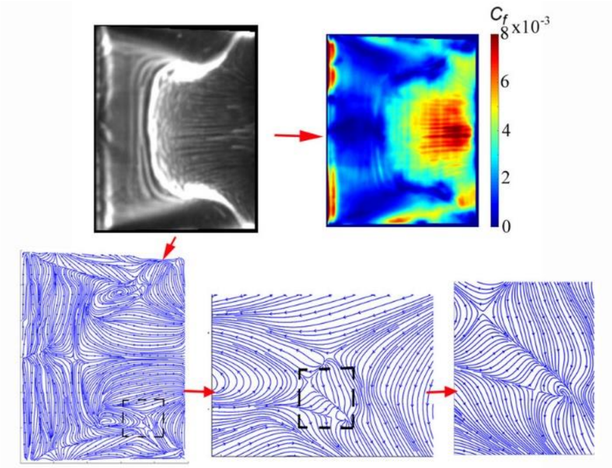
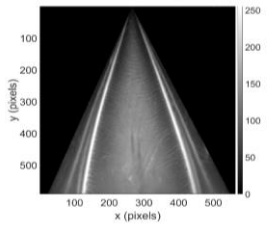


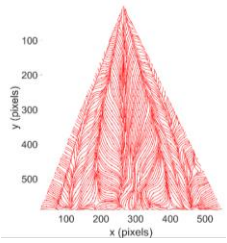
Fig. 2 The flow fields on a low-aspect airfoil

3.2. The flow on a delta wing

A delta wing is a kind of high-speed airplane, which can be seen in many applications. Although the airplane operates mainly at supersonic conditions, the flow on the upper surface under low speed shows many interesting features. A typical flow at upper surface is the existence of two longitudinal vortexes. The separation and reattachment positions on the upper surface of a delta wing can be observed from the oil-film image, as shown in Fig. 3a. However, the secondary separation lines, which occur near the side edges can not be observed from the oil-film image. Those features are clearly shown by the skin-friction lines (Fig. 3b).



a. Luminescent oil



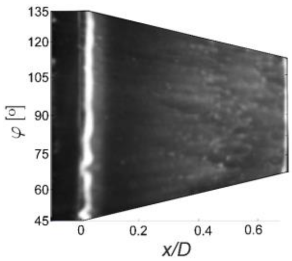
b. Skin friction fields

Fig. 3 Oil film image and skin-friction lines on a delta wing

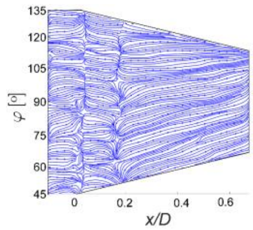
3.3. The flow on an axisymmetric boattail

The axisymmetric blunt-based flow is a typical flow that is featured by a large wake region The boattail, which is understood as an additional geometry added to the base of the model, is known as an effective passive device for drag reduction [8], [9]. Although the geometry of the boattail is simple, the flow behavior is quite different from the case of the blunt-based model. This section tries to extract the skin-friction fields on the slant surface of a boattail surface.

The experiments for skin-friction measurement on boattail surface were conducted at Tohoku University, Japan. The luminescent oil used for the study is mixed on acid oleic and a small mass of chloro-9,10-bis(phenylethynyl)anthracene ($C_{30}H_{17}Cl$) by the proportion of 1000:1. The viscosity is around 37 cSt. The results of the oil film and skin-friction fields are shown in Fig. 4. As we can observe, separation and reattachment lines are formed around the shoulder. Interestingly, many saddle and node points are observed on the critical lines.



a. Luminescent oil



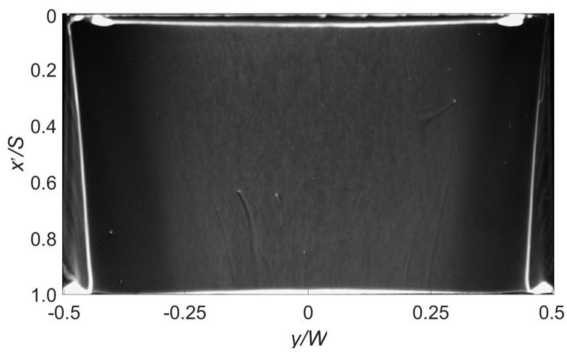
b. Skin friction fields

Fig. 4 Oil film image and skin-friction lines on an axisymmetric boattail model

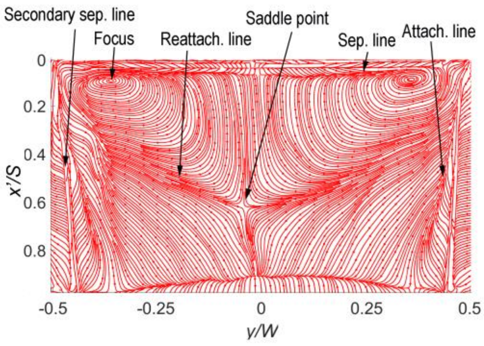
3.4. The flow on a slant surface of road vehicles

The other typical flow feature is the flow on the slant surface of car vehicles, which can be an Ahmed body, typically. For the study, we analyze the surface flow on the slant of the Ahmed body. The slant angle is 25°. The luminescent oil was mixed with silicone oil 10 cSt and luminescent dye by a proposal of 99.5:0.5 by mass. Note that in comparison to the case of boattail flow, the viscosity is much lower. A cover box below the horizontal plate was made to lift down the model during wind tunnel acceleration to prevent the spreading of luminescent oil during the wind tunnel acceleration.

The results of the skin friction streamlines are shown in Fig. 5. Similar to the flow on the upper surface of the delta wing, a complex structure with two longitudinal vortices is observed near the side edges. Those features can be observed well from the oil film image (Fig. 5a). Interestingly, the separation bubble on the slant, which is not shown by luminescent oil, can be illustrated well from the optical-flow program.



a. Luminescent oil



b. Skin friction fields

Fig. 5 Oil film image and skin-friction lines on the slant surface of an Ahmed body

Conclusions

The sub-grid global measurement was applied for extracting skin friction fields in various applications. The results of the current study indicate that the global skin friction fields can be obtained from the measurement technique. The skin-friction magnitude can be also obtained and allow a qualitative discussion of the surface flow. It is also recommended to set up the experimental carefully and selected suitable viscosity for the measurement.

References

[1] D. C. Reda, J. J. Muratore, and J. T. Heineck, “Time and flow-direction responses of shear-stress-sensitive liquid crystal coatings,” *AIAA J.*, vol. 32, no. 4, pp. 693–700, 1994, doi: 10.2514/3.12047.

[2] H. H. Fernholz, G. Janke, M. Schober, P. M. Wagner, and D. Warnack, “New developments and applications of skin-friction measuring techniques,” *Meas. Sci. Technol.*, vol. 7, no. 10, p. 1396, 1996.

[3] T. Liu, J. Montefort, S. Woodiga, P. Merati, and L. Shen, “Global luminescent oil-film skin-friction meter,” *AIAA J.*, vol. 46, no. 2, pp. 476–485, 2008, doi: 10.2514/1.32219.

[4] T. H. Tran and L. Chen, “Wall shear-stress extraction by an optical flow algorithm with a sub-grid formulation,” *Acta Mech. Sin. Xuebao*, vol. 37, no. 1, pp. 65–79, 2021, doi: 10.1007/s10409-020-00994-9.

[5] J. W. Naughton and J. L. Brownt, “Surface interferometric skin-friction measurement technique,” *Adv. Meas. Gr. Test. Conf.*, 1996, doi: 10.2514/6.1996-2183.

[6] T. Lee, T. Nonomura, K. Asai, and T. Liu, “Linear least-squares method for global luminescent oil film skin friction field analysis,” *Rev. Sci. Instrum.*, vol. 89, no. 6, 2018, doi: 10.1063/1.5001388.

[7] L. H. Tanner and L. G. Blows, “A study of the motion of oil films on surfaces in air flow, with application to the measurement of skin friction,” *J. Phys. E.*, vol. 9, no. 3, pp. 194–202, 1976, doi: 10.1088/0022-3735/9/3/015.

[8] W. A. Mair, “[13] Reduction of base drag by boat-tailed afterbodies in low speed flow.pdf,” *Aeronaut. Q.*, vol. 20, pp. 307–320, 1969.

[9]T. H. Tran, T. Ambo, T. Lee, L. Chen, T. Nonomura, and K. Asai, “Effect of boattail angles on the flow pattern on an axisymmetric afterbody surface at low speed,” *Exp. Therm. Fluid Sci.*, vol. 99, pp. 324–335, 2018, doi: 10.1016/j.expthermflusci.2018.07.034.