Open Source Programs for Extraction of Skin Friction Fields from Visualization Images of Surface Quantities

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Abstract

This paper describes "OpenSkinFrictionFromPressure", an open source program in Matlab for extraction of high-resolution skin friction fields from surface pressure images, which is also applicable to visualization images of surface temperature and scalar concentration. This program is a useful tool for researchers to apply the method of skin friction from surface pressure to complex separated flows. The principles of this method are concisely described, including the optical flow equation for visualizations of the surface quantities, the variational solution, an error analysis, and approximate method. The central part of this paper is the descriptions of the main program, relevant subroutines and selection of the relevant parameters in optical flow computation. An example of the square junction flow is given to demonstrate the applications of the method of skin friction from surface pressure.

Keywords: skin friction, surface temperature, surface pressure, surface scalar concentration, optical flow, variational solution, flow visualization, fluid mechanics, measurement technique, image processing, Matlab

(1) Overview

Introduction

Global skin friction diagnostics are based on surface temperature, scalar and pressure visualizations. To extract skin friction from these quantities is an inverse problem [1, 2]. The projection methodology was applied to the energy and mass transport equations for surface heat transfer and mass transfer visualizations with coating techniques (temperature and pressure sensitive paints and sublimating coatings), and relations between skin friction and surface temperature and scalar concentration were obtained [3-6]. Recently, a relation between skin friction and surface pressure was derived from the Navier-Stokes equations [7-9]. These relations can be re-cast into a special form of the optical flow equation in the image plane. Therefore, skin friction fields can be sought as an inverse problem from surface temperature, scalar concentration and pressure images by using the variational method.

The objective of this paper is to describe an open-source programs in Matlab for extraction of high-resolution skin friction fields from images of surface temperature, scalar concentration and pressure. First, the principles of these methods are briefly described, including the generic equation relating skin friction with these surface quantities, the variational method, and a short error analysis. The methods are treated as the optical flow problem. Then, the main program and the key subroutines are described, particularly on the selection of the relevant parameters in optical flow computation. Next, to demonstrate the applications of the programs, several examples are presented.

Principles

a. Optical flow equation

According to Liu [1, 2], for visualizations of surface temperature, scalar concentration and pressure, the relations between skin friction and these surface quantities are written in a generic form, i.e.,

$$G + \boldsymbol{\tau} \cdot \nabla g = 0 , \tag{1}$$

where g and G are the generic measurable quantities, which are defined differently depending on specific visualization technique used in experiments. For example, $G = -\mu f_Q$ and $g = T_w$ for heat transfer visualization, $G = -\mu f_M$ and $g = \phi_1$ for binary mass transfer visualization, and

$G = -\mu f_{\Omega}$ and $g = p$ for surface pressure visualization. The source terms f_Q, f_M and f_{Ω} are discussed by Liu [1, 2], Liu et al. [3-8] and Chen et al. [9]. Eq. (1) has the same form as the Horn-Schunck optical flow equation where $G = \partial g / \partial t$ [10].

The corresponding Euler-Lagrange equation is obtained, i.e.,

$$\left[G + \boldsymbol{\tau} \cdot \nabla g \right] \nabla g - \alpha \nabla^2 \boldsymbol{\tau} = 0 , \tag{2}$$

where α is a Lagrange multiplier, and $\nabla = \partial / \partial x_i$ and $\nabla^2 = \partial^2 / \partial x_i \partial x_i$ $(i = 1, 2)$ are the gradient operator and Laplace operator, respectively.. Given G and g, Eq. (14) can be solved numerically for $\boldsymbol{\tau} = (\tau_1, \tau_2)$ with the Neumann condition $\partial \boldsymbol{\tau} / \partial n = 0$ imposed on a domain boundary ∂D. Since Eq. (1) is valid instantaneously, unsteady skin friction fields can be extracted from unsteady surface temperature, scalar concentration and pressure.

b. Errors

In an error analysis, substitution of the decompositions $g = g_0 + \delta g$, $G = G_0 + \delta G$ and $\boldsymbol{\tau} = \boldsymbol{\tau}_0 + \delta \boldsymbol{\tau}$ to Eq. (2) yields an error propagation equation, where δg, δG and $\delta \boldsymbol{\tau}$ are errors, and g_0, G_0 and $\boldsymbol{\tau}_0$ are the non-perturbed fields that exactly satisfy Eq. (2). A formal estimate of the relative skin friction error $\left(\delta \boldsymbol{\tau} \right)_N = \delta \boldsymbol{\tau} \cdot \boldsymbol{N}_T$ is [3]

$$\frac{\left(\delta \boldsymbol{\tau} \right)_N}{\left\| \boldsymbol{\tau}_0 \right\|} = -\frac{\delta G}{\left\| \nabla g_0 \right\| \left\| \boldsymbol{\tau}_0 \right\|} - \left(\frac{\boldsymbol{\tau}_0}{\left\| \boldsymbol{\tau}_0 \right\|} \right) \cdot \delta \boldsymbol{N}_T + \frac{\alpha}{\left\| \nabla g_0 \right\|^2} \nabla^2 \left[\frac{\left(\delta \boldsymbol{\tau} \right)_N}{\left\| \boldsymbol{\tau}_0 \right\|} \right] , \tag{3}$$

where $\left\| \boldsymbol{\tau}_0 \right\|$ is a mean value of skin friction, and $\boldsymbol{N}_T = \nabla g_0 / \left\| \nabla g_0 \right\|$ is the unit normal vector to an iso-value line $g_0 = const.$. The first term in the RHS of Eq. (3) is the contribution from the elemental error in measurement of *G*. The second term is the contribution from the elemental error in measurement of the surface gradient of the relative intensity. The third term is the contribution from the artificial diffusion of $(\delta\boldsymbol{\tau})_N$ associated with the Lagrange multiplier. Since the first term in the RHS of Eq. (3) is proportional to $\|\nabla g_0\|^{-1}$, the relative error $(\delta\boldsymbol{\tau})_N / \|\boldsymbol{\tau}_0\|$ increases as $\|\nabla g_0\|$ decreases. The third term is proportional to $\alpha\|\nabla g_0\|^{-2}$, indicating that the Lagrange multiplier α must be sufficiently small to reduce the error particularly when $\|\nabla g_0\|$ is small.

c. Approximate method

Since the source term G is not known exactly, the approximate method is applied to the problem of extracting skin friction from the surface quantity. First, in the zeroth-order approximation, a known base flow (such as a boundary layer flow) is considered, which satisfies

$$G^{(0)} + \boldsymbol{\tau}^{(0)} \cdot \nabla g^{(0)} = 0 , \tag{4}$$

where the superscript '0' denotes the base flow. A composite g-field (or a perturbed g-field) on a surface is given by

$$g^{(1)} = g^{(0)} + \Delta g , \tag{5}$$

where Δg is the g-variation.

The first-order $\boldsymbol{\tau}$-field denoted by $\boldsymbol{\tau}^{(1)}$ can be described by the first-order approximate equation

$$G^{(0)} + \boldsymbol{\tau}^{(1)} \cdot \nabla g^{(1)} = 0 , \tag{6}$$

where $G^{(0)}$ is the base-flow source term. Therefore, a $\boldsymbol{\tau}^{(1)}$-field can be obtained by solving the Euler-Lagrange equation, Eq. (6), with the known source term for the base flow $G = G^{(0)}$. For iterative improvement in successive higher-order approximations, a heuristic iteration scheme is

$$G^{(k)} = -\boldsymbol{\tau}^{(k)} \cdot \nabla g^{(k)} . \ (k = 1,2,\cdots)$$

The base-flow surface temperature and its gradient are given by

$$g^{(0)} = c_0 + (c_1 / 2m)(x - x_0)^{2m} , \ \ \partial g^{(0)} / \partial x = c_1 (x - x_0)^{2m-1} , \tag{7}$$

where c_0 and c_1 are proportional coefficients, x_0 is the virtual origin of the boundary layer, and m is a power-law exponent. Accordingly, skin friction and the source term in the base flow are given in the power-law relations, i.e.,

$$\tau^{(0)} = c_2 (x - x_0)^{(3m-1)/2} , \ \ G^{(0)} = c_3 (x - x_0)^{(7m-3)/2} , \tag{8}$$

where c_2 and c_3 are proportional coefficients. The power-law distributions of surface scalar concentration, skin friction and source term serve as a local approximation in laminar and turbulent flows in applications. The parameters m and x_0 can be determined by fitting surface scalar concentration data. In general, when these proportional coefficients are not given, a $\boldsymbol{\tau}$-field obtained by this approximate method is a relative field or normalized field.

Implementation and architecture

The program package "OpenSkinFrictionFromPressure_v1" is written in Matlab, which is available in the GitHub site: XX. This program is used for extraction of skin friction fields from surface pressure fields, which is also applicable to fields of surface temperature and scalar concentration since the optical flow equation is the same for the tree surface quantities. The main program is "Skin_Friction_from_Pressure_Run.m". The central part is the optical flow computation using the subroutine "Optical_Flow_generic.m" that is a solver for the Euler-Lagrange equation Eq. (2). The subroutine "p_bef_images_base_flow_power_law.m" is used to generate the images of surface pressure, boundary enstrophy flux (BEF) and skin friction with the power-law distributions in the main stream direction in the base flow. The subroutine "Superposition_base_variation_image.m" generates the composite surface pressure image (the $g^{(1)}$-field) and the corresponding base-flow BEF image (the $G^{(0)}$-field).

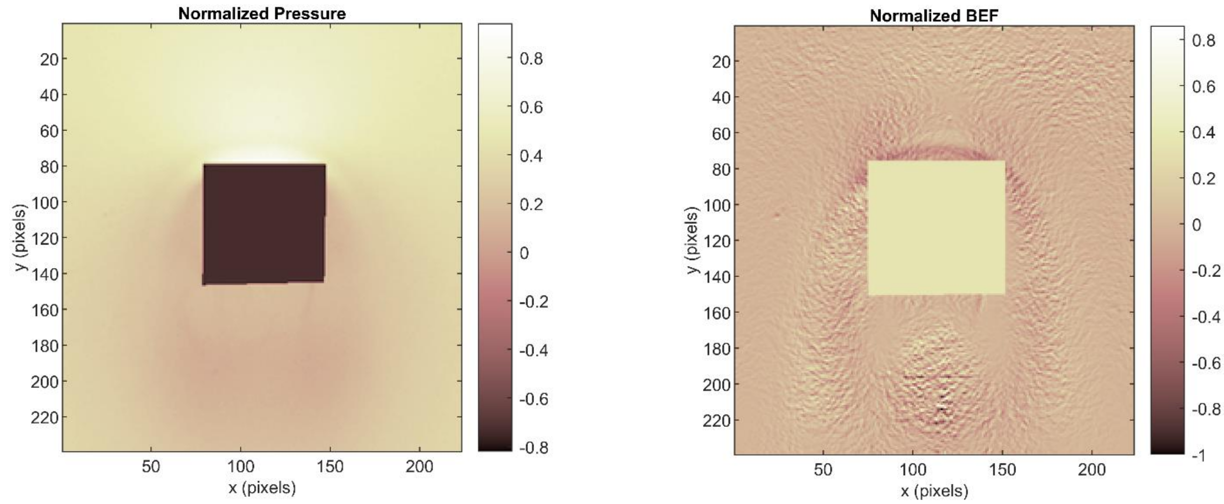
In "Skin_Friction_from_Pressure_Run.m", the composite surface pressure image (the $g^{(1)}$-field) and the base-flow BEF image (the $G^{(0)}$-field) are loaded. The Lagrange multiplier "lambda" is given (for example 10^{-4}). There is no rigorous theory for determining the Lagrange multiplier. In general, the smallest Lagrange multiplier that still leads to a well-posed solution could be selected by a trial-and-error process.

Example: square junction flow

PSP measurements were conducted in the Tohoku-University Basic Aerodynamic Research Wind Tunnel [11]. This is a suction-type wind tunnel that has a solid wall test section of 300 mm width, 300 mm height and 760 mm length. In junction flow measurements, the test model was a 3D square cylinder that has 40×40 mm cross-section and 100 mm height. The test model was vertically mounted on the flat plate and could be rotated by a turntable. PSP measurements were conducted mainly on the floor around the model. The free-stream velocity was set at 50 m/s in PSP measurement. The incident angle relative to the free-stream was set at 0 degrees for the square cylinder. The Reynolds number based on the model length was $Re_D = 1.3\times10^5$ for the square cylinder and 1.8×10^5 for the diamond cylinder. The local Reynolds number is $Re_x = 7.8\times10^5$ for the location of the front of the cylinder at 230 mm from the flat-plate leading edge.

It was confirmed by hot-wire measurement that the incoming boundary layer was laminar state under these conditions.

Figure 1(a) shows a normalized surface pressure field obtained from PSP measurements in this junction flow. For comparison, GLOF skin friction diagnostics were conducted at the same test conditions, where perylene-mixed silicone oil was used. From this extracted skin friction field and the surface pressure field obtained by using PSP, a BEF field is reconstructed by using the relation $f_{\Omega} = \mu^{-1}\boldsymbol{\tau} \cdot \nabla p$. Figure 1(b) shows the BEF field reconstructed from PSP and GLOF measurements. Then, from the surface pressure field and BEF field, a skin friction field is extracted by solving Eq. (2). Figure 2 shows extracted skin friction lines, exhibiting interesting skin friction topology on the floor surface. A saddle is located at the upstream of the square cylinder, from which the primary necklaced separation line is originated. In addition, attachment lines are originated from the sides of the cylinder. The primary separation and attachment lines are associated with a single large horseshoe vortex forming in the front of the cylinder. Behind the cylinder, a combination of the saddle and the spiraling sink nodes (foci) are observed, which are the time-averaged on-wall footprints of the shedding wake structures.



(a) (b)

Figure 1. (a) Surface pressure image, and (b) BEF image in the square junction flow.

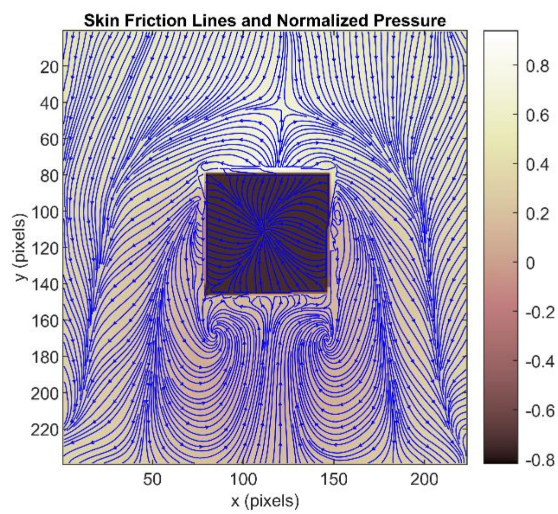


Figure 2. Time-averaged skin friction lines in the square junction flow, extracted from the surface pressure and BEF images in Fig. 1.

(2) Availability

Operating system

Based on Matlab (R2007a, or later versions): Windows

Programming language

Matlab (R2007a, or later versions)

Additional system requirements

None

Dependencies

Several functions in Matlab image processing toolbox are required.

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Software location

Name: GitHub

Identifier:

License: MIT license

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(3) Reuse Potential

Global skin friction diagnostics is of fundamental importance in the study of fluid mechanics in order to understand the physics of complex flows. The global luminescent oil-film (GLOF) method allows extraction of high-resolution skin friction fields from GLOF images obtained in various complex flows. The experimental setup for GLOF measurements is simple, and the GLOF images could be obtained by using inexpensive CCD and CMOS cameras under suitable illumination (such as UV light). The foundation of the GLOF method is well established based on the thin-oil-film equation projected onto the image plane. GLOF computation can be conducted in a PC with Matlab to extract skin friction fields at a spatial resolution of one vector per pixel. The GLOF method has been applied to complex separated flows. This open source program, "OpenSkinFrictionFromGLOF", allows users to adapt the GLOF method for their specific problems. Furthermore, "OpenSkinFrictionFromGLOF", can be integrated with Matlab for convenient image processing, data presentations, and data input/output. Besides GitHub, the programs can be directly downloaded from the author's website https://wmich.edu/mechanical-aerospace/directory/liu.

References:

[1] Liu T (2013) Extraction of skin-friction fields from surface flow visualizations as an inverse problem. Meas Sci Technol 24:124004.

[2] Liu T (2018) Skin-friction and surface-pressure structures in near-wall flows. AIAA J 56(10):3887-3896.

[3] Liu T, Woodiga S (2011) Feasibility of global skin friction diagnostics using temperature sensitive paint. Meas Sci Technol 22:115402.

[4] Liu T, Woodiga S, Gregory J and Sullivan JP (2014) Global skin friction diagnostics based on surface mass-transfer visualizations. AIAA J 52(11):2369-2383.

[5] Liu T, Makhmalbaf MHM, Ramasamy RSV, Kode S, Merati P (2015b) Skin friction fields and surface dye patterns on delta wings in water flows. J Fluids Eng 137:071202.

[6] Miozzi, M, Capone A, Di Felice A, Klein C and Liu T (2016) Global and local skin friction diagnostics from TSP surface patterns on an underwater cylinder in cross flow. Phys Fluids 28(12):12410.

[7] Liu T, Misaka T, Asai K, Obayashi S, Wu JZ (2016) Feasibility of skin-friction diagnostics based on surface pressure gradient field. Meas Sci Technol 27(12):125304.

[8] Liu T (2018) Skin-friction and surface-pressure structures in near-wall flows. AIAA J 56(10):3887-3896.

[9] Chen T, Liu T, Wang L-P and Chen SY (2019) Relations between skin friction and other surface quantities in viscous flows. Phys Fluids 31:107101.

[10] Horn B K, Schunck B G (1981) Determining optical flow. Artificial Intelligence 17:185-204.

[11] Kakuta T, Koyama A, Yorita D, Numata D, Nagai H, Asai K, Woodiga SA and Liu T. Imaging measurement of skin friction field around bluff body using luminescent oil film technique. ISFV14 - 14th International Symposium on Flow Visualization, June 21-24, 2010, Daegu, Korea.