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Separation flow control

Experimental detection of flow separation over a plain flap by wall shear stress analysis with and without steady blowing

Détection expérimentale du décollement de l'écoulement sur un volet sans fente par l'analyse du frottement pariétal avec ou sans soufflage continu

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A B S T R A C T

The present article deals with the flow separation detection over a plain flap at a Reynolds number of $2 \cdot 10^6$ by the analysis of the wall shear stress fluctuations. Natural flow separation is first considered with the study of the evolution of wall shear stress fluctuations measured along the flap chord when the flap deflection angle is progressively increased. Then, steady blowing is applied and its effect on wall shear stress fluctuations is analysed. For both controlled and uncontrolled cases, flow separation criteria are defined, studied and compared.

R É S U M É

Cet article traite de la détection du décollement de l'écoulement sur un volet sans fente pour un nombre de Reynolds de $2 \cdot 10^6$ par l'analyse des fluctuations du frottement pariétal. On considère en premier lieu le décollement naturel à travers l'étude de l'évolution des fluctuations de frottement pariétal mesurées sur la corde du volet lorsque son angle de braquage augmente progressivement. Par la suite, un contrôle par soufflage continu est appliqué et l'effet de ce contrôle sur les fluctuations de frottement pariétal est étudié. Dans les cas contrôlé et non contrôlé, des critères de décollement sont définis, étudiés et comparés entre eux.

1. Introduction

Measurement of wall shear stress has been hardly used to detect flow separation occurring on aerofoils since the early studies of Stack et al. [1] and Nakayama et al. [2]. Shear stress can be measured by non-intrusive devices such as hot films, however. This is particularly interesting for studies aiming at detecting flow separation within a scope as close to

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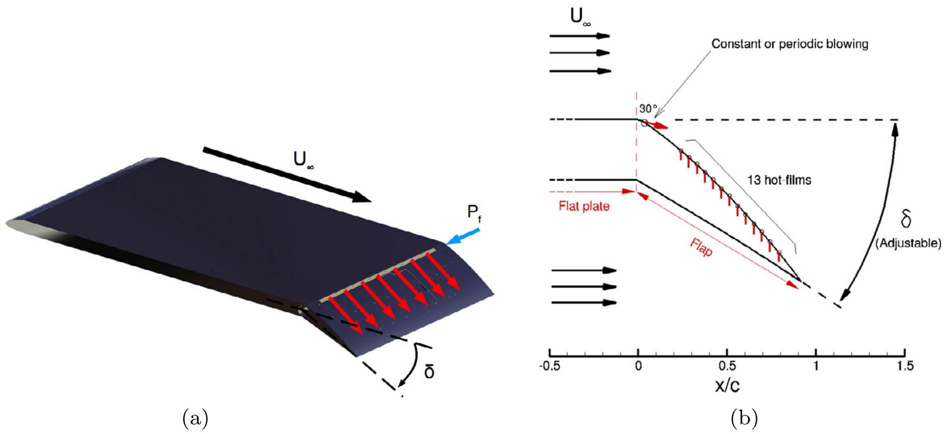

Fig. 1. (Color online.) (a) Wind tunnel model and (b) schematic view of hot films' position.

real application as possible. Therefore, several studies ([3–7]) concerning closed-loop control of flow separation has brought a renewed interest for the research of a detection technique based on wall shear stress. Some authors (Poggie et al. [4] and Shaqarin et al. [6]) propose to base the flow separation detection upon a calibration of the hot films. In this case, the success of flow separation detection relies on the suitable choice of a threshold value that enables one to determine the flow state from the current measurement of wall shear stress. Other authors (Rethmel et al. [5], Packard & Bons [3] and Troshin & Seifert [7]) prefer to use the rms value (or a calculated value assimilated to the rms value) to detect flow separation. Indeed, flow separation is generally marked by a sharp increase of the rms value of hot-film voltage, as shown by Pack et al. [8] and Seifert & Pack-Melton [9]. One advantage of the rms method over the calibration-based method is that the hot films do not need to be calibrated in the former case. Nevertheless, the definition of a threshold on the rms value is still needed in order to determine the flow state according to the rms current value. Furthermore, Nakayama et al. [2] and Meijering & Shroder [10] propose a "two-point" approach since they suggest to calculate the correlation coefficient between the signals of two adjacent hot films. This technique does not need any threshold to be defined since the correlation coefficient is supposed to be simply zero when the flow separation point is located between the two sensors that are considered for detection. However, this method requires two sensors instead of one. Finally, a last detection technique based on the skewness estimation is proposed by Cuvier et al. [11]; this technique is all the more interesting regarding the scope of present study, since it is used to detect flow separation in both uncontrolled and controlled cases.

In the present work, different variables are calculated from the wall shear stress fluctuations measured on the chord of a deflected plain flap on which flow separation naturally occurs. The idea is to evaluate those variables as candidates to define suitable criteria for flow separation detection in both uncontrolled and steady-blowing-controlled cases. The article is divided into three parts. The experimental set-up is first presented in Section 2. In Section 3, the flap is progressively deflected and the natural flow separation that is produced is first revealed through the study of wall pressure distributions. Based on this revelation, wall shear stress fluctuations are studied and the evolutions of several variables calculated from hot-film voltages are linked with the development of flow separation. Then, steady blowing is applied in Section 4 and its impact on wall shear stress fluctuations is studied in order to reveal the flow separation delay due to flow control.

2. Experimental apparatus

The experiments are performed in the S_2L Eiffel-type wind tunnel located at the ONERA Chalais–Meudon research centre. For more details on the experimental set-up, the reader can refer to Ref. [12]. The test model is presented in Fig. 1(a) and consists of an 867-mm-long flat plate and a plain flap (chord length $c = 220$ mm), based on a NACA 4412 airfoil shape. It is placed inside a cylindrical slightly divergent 1750-mm-long test section. The model covers the 800 mm of the wind tunnel span. Carborundum is used at its leading edge to trigger transition. Surface-oil-flow visualisations have shown that the set-up is two dimensional on 80% of the span. The wind tunnel tests are performed at an average free-stream velocity $U_\infty = 24.5\ \mathrm{m\,s^{-1}}$, giving a Reynolds number $Re_{\mathrm{model}} = 2 \cdot 10^6$ based on the total length of the model. The external turbulence level is 0.2% (see Gand et al. [13] and Brion [14]). The wind tunnel model is installed with a zero angle of attack and the flap can be deflected by a positioning system according to the angle δ from 2 to 37°. The deflection angle is denoted by δ. Thirteen Senflex® hot-film sensors are chordwise (single row) and regularly bonded on the flap (see Fig. 1b). They are regulated by three Dantec® *Streamlines* and the corresponding voltage signals are simultaneously acquired and digitised by a NI PXIe-6358 data acquisition card at a sampling rate of 10 kHz. The signals are low-pass filtered at 3 kHz to avoid aliasing. The signal acquisition lasts for 40 s. Welch's periodogram method is used to estimate the power spectral densities presented in the following. The signals are divided into 79 blocks with 50% overlap, so the resolution is of 0.6 Hz.