C. R. Mecanique 342 (2014) 376–381

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Separation flow control

# Flow control on a 3D backward facing ramp by pulsed jets

## *Contrôle d'écoulemement dans le sillage d'une rampe descendante 3D par jets pulsés*

Pierric Joseph [a,*], Dorian Bortolus [a], Francesco Grasso [a,b]

[a] *Institut aérotechnique (IAT–CNAM), 15, rue Marat, 78210 Saint-Cyr-l'École, France*
[b] *CNAM, Laboratoire DynFluid, 151, boulevard de l'Hôpital, 75013 Paris, France*

A R T I C L E I N F O

*Article history:*
Received 26 July 2013
Accepted 14 December 2013
Available online 21 June 2014

*Keywords:*
Flow control
Pulsed jets
Backward facing ramp
PIV

*Mots-clés :*
Contrôle d'écoulement
Jets pulsés
Rampe descendante

A B S T R A C T

This paper presents an experimental study of flow separation control over a 3D backward facing ramp by means of pulsed jets. Such geometry has been selected to reproduce flow phenomena of interest for the automotive industry. The base flow has been characterised using PIV and pressure measurements. The results show that the classical notchback topology is correctly reproduced. A control system based on magnetic valves has been used to produce the pulsed jets whose properties have been characterised by hot wire anemometry. In order to shed some light on the role of the different parameters affecting the suppression of the slant recirculation area, a parametric study has been carried out by varying the frequency and the momentum coefficient of the jets for several Reynolds numbers.



R É S U M É

Ce travail présente une étude expérimentale du contrôle d'un décollement dans le sillage d'une rampe descendante 3D par jets pulsés. Cette géométrie a été choisie pour reproduire un écoulement d'intérêt pour l'industrie automobile. L'écoulement de base a été caractérisé par PIV et mesures de pression. Les résultats montrent que la topologie de type tricorps est correctement reproduite. Un système de contrôle basé sur des électrovannes a été utilisé pour créer les jets pulsés, dont les propriétés ont été caractérisées par anémométrie à fil chaud. Afin d'éclairer le rôle des paramètres affectant la suppression de la zone décollée, une étude paramétrique a été menée en changeant la fréquence et la quantité de mouvement injectée pour différents nombres de Reynolds.



* Corresponding author.
*E-mail address:* pierric.joseph@cnam.fr (P. Joseph).

http://dx.doi.org/10.1016/j.crme.2013.12.010
1631-0721/© 2014 Published by Elsevier Masson SAS on behalf of Académie des sciences.

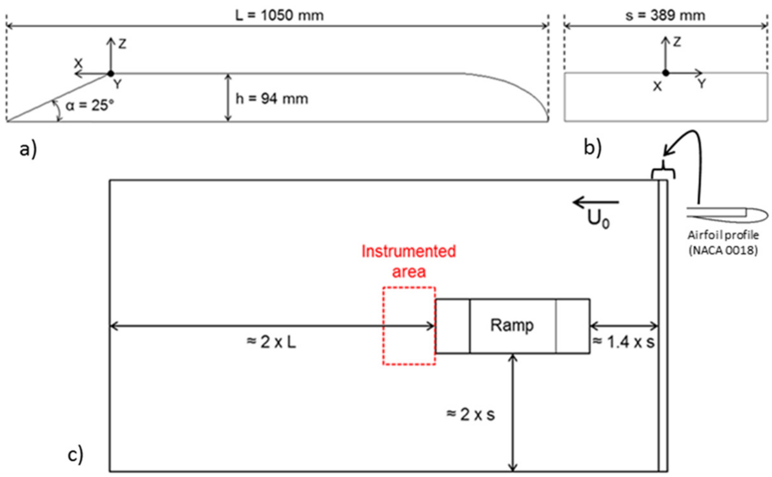


**Fig. 1.** (Colour online.) Side (a) and front (b) views of the backward facing ramp; (c) top view of the elevated floor with model arrangement.

## 1. Introduction

### *1.1. Context*

Today environmental issues demand a drastic reduction of both pollutants emissions and fuel consumption. These issues are of great importance for the transport industry, especially for automotive manufacturers. When considering high speed displacements like highway travelling, drag reduction with the constraints of security and design is indeed one of the main concerns of the automotive industry. Active flow control, relying on an external energy source, has been shown to be an effective means to modify the flow around various bodies [1], including automotive shapes. Different techniques can be found in the literature, like moving walls [2], plasma actuators [3], or the ones based on the use of jets. Continuous blowing or suction has been applied for a long time in aeronautics [4], and both are studied for automotive applications [5,6]. Periodic blowing (either pulsed or synthetic jets) appears to be a much more efficient solution [7] at the cost of a greater complexity. Even though the technic is successfully applied in automotive related studies [8–10], it needs to be further investigated, especially to optimise the efficiency of the control action in full 3D cases with finite spanwise (which are closer to the industrial cases).

In the present work, we have carried out an experimental study of flow separation control over a 3D backward facing ramp by means of pulsed jets. Such geometry has been selected to reproduce flow phenomena of interest for the automotive industry. In the following, we first characterise the base flow through PIV and pressure measurements. We then describe the control system and characterise the properties of the pulsed jets by hot wire anemometry. Finally, we present results of flow control through a parametric study whereby the frequency and the momentum coefficient of the jets were varied for several Reynolds numbers.

### *1.2. Experimental setup*

Experiments were carried out in the S4 wind tunnel of the Institut aérotechnique (IAT–CNAM, France). The S4 test cross section is 5 m × 3 m, and the flow velocity ($U_0$) ranges from 20 $\mathrm{m\,s^{-1}}$ to 40 $\mathrm{m\,s^{-1}}$ with a maximum turbulent intensity of 1.2%. The model geometry is depicted in Fig. 1 (observe that all dimensions are in millimetres). In order to minimise the effect of the boundary layer developing on the floor of the tunnel, the ramp lays on an elevated floor (see Fig. 1c) with an airfoil-shaped leading edge to prevent separation. This elevated floor presents an instrumented area as flow structures expands farther in the wake.

With this arrangement, upstream of the separation point the boundary layer thickness is $\delta_{99} = 27 \times 10^{-3}$ m (measurements carried out with total pressure probe at $X = -5 \times 10^{-2}$ m, $Y = 9.5 \times 10^{-2}$ m). Oil flow visualisation of the base flow (discussed in the next section) confirmed that the flow is symmetric on average. Therefore, only half of the rear part of the model (both the slant and the instrumented area of the elevated floor) was instrumented with 141 pressure taps. Wall pressure measurements were obtained by using a scanivalve pressure scanner (accuracy: 0.03%), and the results are expressed in terms of the pressure coefficient $C_p = (p - p_0)/(\frac{1}{2}\varrho U_0^2)$, where $p$ and $p_0$ are, respectively, the local and undisturbed static pressure, and $\frac{1}{2}\varrho U_0^2$ is the dynamic pressure. PIV measurements were realised using an Nd:YAG laser (200 mJ, 15 Hz) and a FlowSense EO 4M camera. Oil droplets (average size: 2 μm) were used to seed the flow. The velocity field was characterised both in the streamwise ($XZ$) and spanwise ($YZ$) directions; the dimensions of the measurement planes are: 0.56 m × 0.56 m in the $XZ$ plane, and 0.46 m × 0.46 m in the $YZ$ plane, with 2048 × 2048 pixels resolution. The velocity