Journal of Aircraft
Vol. 46, No. 3, May–June 2009

Flow Measurements in a Short Takeoff, Vertical Landing Fountain: Splayed Jets

A. J. Saddington,* K. Knowles,† and P. M. Cabrita‡
Cranfield University, Shrivenham, Swindon SN6 8LA, United Kingdom

DOI: 10.2514/1.38296

The interaction of multiple jets with the ground is of great importance for the design and operation of short takeoff, vertical landing aircraft. The fountain upwash flow, generated by the impingement of two axisymmetric, compressible, turbulent jets onto a ground plane was studied using laser-based particle image velocimetry. Measurements were made with nozzle pressure ratios of between 1.05 and 4, nozzle height-to-diameter ratios of between 2.4 and 8.4, nozzle splay angles of between ±15 deg, and a nozzle spacing-to-diameter ratio of seven. The effect of varying these parameters on the fountain velocity decay, spreading rate, and momentum flux ratio are discussed. In general, it was found that the inclusion of nozzle splay did not significantly alter the distribution of fountain momentum flux ratio relative to the equivalent parallel configuration.

Nomenclature

a_1	=	growth rate of the fountain half-width (see Eq. (4))
a_2	=	fountain half-width at $z = 0$ (see Eq. (4))
D	=	nozzle exit internal diameter
H	=	nozzle exit height above the ground plane (see Fig. 1)
J	=	proportion of jet momentum carried downstream after impingement (i.e. downstream momentum divided by total jet momentum)
L	=	theoretical distance between the jets' stagnation points at impingement (see Fig. 1)
$\dot{M}$	=	fountain momentum flux
$\dot{M}_{\max}$	=	maximum fountain vertical momentum flux
r	=	radial distance from the nozzle axis
S	=	distance between the nozzle centers (see Fig. 1)
U	=	time–mean velocity in the streamwise direction
$\hat{U}$	=	time–mean peak streamwise velocity in the fountain
U_j	=	time–mean jet centerline velocity at the nozzle exit
$U_{\max}$	=	time–mean local maximum streamwise velocity in the fountain
u	=	instantaneous velocity in the streamwise direction (positive downwards for jets; positive upwards for fountain)
v	=	instantaneous velocity in the x-direction
x	=	coordinate parallel to the ground plane in the plane of the jet centers (see Fig. 1)
$x_{0.5}$	=	fountain half-width where $U = U_{\max}/2$
x_1	=	fountain width
y	=	coordinate parallel to the ground plane in the plane of the nominal fountain axis (see Fig. 1)
z	=	coordinate normal to the ground plane (see Fig. 1)
α	=	nozzle splay angle (positive outwards)
$\lambda_{\dot{M}}$	=	fountain momentum flux ratio ($\dot{M}/\dot{M}_{\max}$)
ρ	=	air density
ϕ	=	jet spreading half-angle (see Fig. 1)

Received 28 April 2008; revision received 19 December 2008; accepted for publication 19 December 2008.

*Lecturer, Defence Academy of the United Kingdom, Aeromechanical Systems Group.

†Professor, Defence Academy of the United Kingdom, Head of Aeromechanical Systems Group. Associate Fellow AIAA.

‡Research Student, Defence Academy of the United Kingdom, Aeromechanical Systems Group.

Introduction

ROTATING the nozzles on the propulsion system of a short takeoff, vertical landing (STOVL) aircraft into a splayed configuration (Fig. 1), and thereby altering the vertical component of thrust, provides a means by which the rate of ascent or descent during vertical flight may be controlled. Such a technique overcomes the inherent lag in the turbomachinery, enabling a more rapid response to control demands, which may be important when operating in close proximity to the ground. Splay may also be used to change the strength of the fountain; splaying the jets away from each other reduces the fountain vertical momentum, whereas splaying them inwards increases it [1]. If the jets are splayed inwards such that they merge before impingement with the ground, then no fountain formation occurs. The ability to schedule splay angle with, for example, aircraft height above the ground, provides the opportunity to trade off the beneficial lift-enhancing properties of the fountain flow against its detrimental hot gas ingestion and acoustic fatigue characteristics.

Whilst there have been numerous experimental studies of the fountain flow generated by parallel impinging jets, far fewer have addressed configurations where the jets are splayed. Notable contributions are included in [2–4], however, even these did not focus to any great extent on the effect of splay, regarding it as supplementary to the main investigation of parallel jets. The studies concluded that, in general, outward splay of the jets reduces fountain peak vertical velocity and turbulence intensity. Conversely, inward splay had the opposite effect; fountain vertical velocity and turbulence intensity was increased. This paper addresses the need for a better understanding of the effect of splaying the jets on fountain behavior.

Aims and Objectives

The continued development of STOVL aircraft, both manned and unmanned, with an increasing reliance on computational design techniques, is dependent upon a better understanding of the aerodynamics of jet-lift aircraft in ground effect. The aim of this work was to describe and quantify the fountain upwash flowfield (generated by a pair of impinging, turbulent, compressible jets) in the plane connecting the nozzle centerlines for a range of geometries and nozzle pressure ratios (NPRs). The objectives of the work were to analyze and quantify the effect of nozzle splay angle on

1) jet impingement;
2) the mean flowfield characteristics;