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Suppression of Cavity Loads Using Leading-Edge Blowing

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We present hybrid Reynolds-averaged Navier–Stokes/large eddy simulation-based analysis of the suppression of fluctuating pressure loads on the walls of a complex nonrectangular cavity using leading-edge mass blowing. The unique aspect of the concepts discussed here is the very low mass flow rates used to achieve significant suppression. The simulation results are used to gain insight into the mechanism governing the effectiveness of these jets. The jets are applied to an $L/D = 5.6$ cavity at supersonic conditions of Mach 1.5. The simulation results show excellent agreement with experiments demonstrating an overall reduction in fluctuating pressure levels on the order of 50% with the control concepts. The primary mechanism of reduction is the break up of the spanwise coherence in the shear layer into smaller vortical structures thus reducing the shear layer flapping and leading to a smaller imprint on the wall pressures.

Nomenclature

C_μ	=	momentum coefficient
f_m	=	frequency of mth Rossiter mode
L	=	cavity length
m	=	mode number
m_j	=	mass flow rate of jet
M_∞	=	freestream Mach number
N	=	number of jets
Q	=	freestream dynamic pressure
St_m	=	Strouhal number of mth Rossiter mode
U_j	=	jet velocity
$U_{\max}$	=	maximum velocity at station
$U_{\min}$	=	minimum velocity at station
U_∞	=	reference velocity
w	=	width of cavity leading edge
α, K	=	modified Rossiter formula constants
δ	=	thickness of upstream boundary layer
δ_w	=	vorticity thickness
$\frac{\partial u}{\partial y}\vert_{\max}$	=	maximum velocity gradient at station
ρ_∞	=	reference density

I. Introduction

EXTERNAL weapons' carriages can be responsible for as much as 30% of the total vehicle drag and lead to prohibitive increases in radar signatures of current generation combat aircraft [1]. Motivated by these considerations, recent military aircraft programs have incorporated internal weapons' carriage systems. However, an internal aircraft weapons bay, when exposed to freestream flow, experiences an intense aeroacoustic environment in and around the bay [2] with unsteady pressure fluctuations as high as 160 to 180 dB. Similar cavity oscillations due to nonlinear instability wave interactions are also present in wheel wells and sensor bays in a high-speed environment. High-fluctuating pressure loads can significantly reduce the life of aerostructures in the bay and can damage sensitive electronic components. Aircraft design engineers are being challenged to develop innovative suppression methods to control the environment in the weapons bay associated with the large fluctuating pressures.

Over the years, aircraft structural design engineers have tested varied passive suppression concepts for effectiveness in attenuation of dynamic loads within the bay, for example, a small spoiler located upstream of the cavity [3], other leading- and trailing-edge devices [4], porous spoilers, [5], a small fence [6], an oscillating flap [7], etc. Passive control methods are inexpensive, simple, and, at certain flow conditions, very effective in suppressing the cavity oscillations. However, the performance of the suppression device at off-design or during time-dependent conditions (maneuvering aircraft) can degrade significantly and cavity loads might be higher than without control. Active control methods, although more complex, have the potential of adapting to differing flow conditions and, thus, can provide suppression of oscillations over the full flight spectrum. Mass injection at the leading edge of the cavity offers great potential to achieve this.

Over the past few years, several studies have been carried out (see Cattafesta et al. [8] and Rowley and Williams [9] for recent reviews) to examine the use of leading-edge mass blowing concepts to suppress the dynamic loads on the surfaces of cavities. Several of these concepts have demonstrated success, suppressing the loads by over 10 dB in many cases. However, most of these mass blowing concepts have involved the use of significant amounts of mass flow rates, rendering them impractical for full-scale applications. More recently, Zhuang et al. [10,11] and the authors and their collaborators [12–14] have demonstrated the use of low mass flow rate blowing concepts for control of cavity loads. These works have demonstrated suppression exceeding that achieved by currently deployed spoiler-type configurations. In addition, this success has been repeated at several scales and shown to have a positive effect on store separation [15], thus, rendering them very attractive in comparison to spoiler-type devices. In the present paper we examine the physical mechanisms underlying the successful suppression achieved by the use of such leading-edge blowing devices. We focus on the low supersonic regime, and all the cases in the present paper have been carried out at Mach number 1.5.

The paper is organized as follows: in Sec. II we first describe the flow configuration and simulation setup. A brief description of the

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