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SYSTEMS ARCHITECTURE AND IMPLEMENTATION COSTS OF SWEEPING JET ACTUATORS FOR SEPARATION CONTROL

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INTRODUCTION

Aerodynamic gains offered by active flow control (AFC) can be maximized if AFC system design is included as part of the initial aircraft design optimization process. In the more likely scenario in which the inception of AFC systems is initially via retrofitting to existing aircraft, implementation will largely be dictated by whether such systems can be installed within the available mass, power and space constraints. The motivation for this study is to understand the associated systems costs of incorporating an array of sweeping jet actuators in an Airbus A320 aircraft for the purpose of separation control along the trailing edge (TE) flap.

Sweeping jet actuators (SWJAs), also known as fluidic oscillators, are based on the bi-stable states of a jet of fluid in a cavity caused by a specially designed feedback path (Fig. 1a). The SWJA design is such that it can produce an oscillating jet (1-20 kHz) of high exit velocity (~sonic flow) and low mass flow rate (~1 g/s) from a meso-scale nozzle (200 μm – 1 mm) with no moving parts [1,2]. SWJAs have demonstrated effectiveness to control separation on various flap geometries [3] and, due to a relatively high level of technology readiness, have been selected for full-scale flight tests on the Boeing 757 vertical tail 'ecoDemonstrator' program.

Research has been undertaken to understand the nature of the systems architectures needed to support the generation, management and distribution of power to AFC actuators for civil transport aircraft applications [4]. There is benefit in delivering power electrically to fluidic actuators such as SWJAs (via localized compressors) rather than pneumatically (via direct engine bleed), namely in the form of reduced distribution costs (mass and volume) and greater compliance with a perceived shift towards more-electric, zero-bleed aircraft [5]. An electrical systems architecture to support an SWJA array (Fig. 1b) thus forms the basis of this study.

METHODOLOGY

The present work uses a scalable, low-order system mass model [4], as defined in (1):

$$m = (W_F / \eta)[\Sigma m_w(\eta) + \dot{m}w_g t], \qquad (1)$$

The overall system mass, m, is equal to the sum of the AFC hardware system masses and the mass cost of the energy used by the system. The former is made up of scalable power-specific mass terms, m_w, for each generation, management, distribution and actuation subsystems that constitute the systems architecture, whereas the latter is the mass of the fuel used for the duration of AFC operation, t, and is determined from the power-specific fuel consumption of the generator system, $\dot{m}w_g$. The m_w and $\dot{m}w_g$ terms have units of kg/kW and kg/s/kW respectively and are multiplied in (1) by the overall power requirement, which is equivalent to the SWJA array fluid output power, W_F, divided by the overall power efficiency of the system, η, to give total system mass. The fluid power delivered by an array of n SWJAs is given in (2):

$$W_F = \frac{\pi}{4}\frac{(VR)^3\Delta}{\lambda}\frac{1}{2}\rho s_A \delta U_\infty^3, \qquad (2)$$

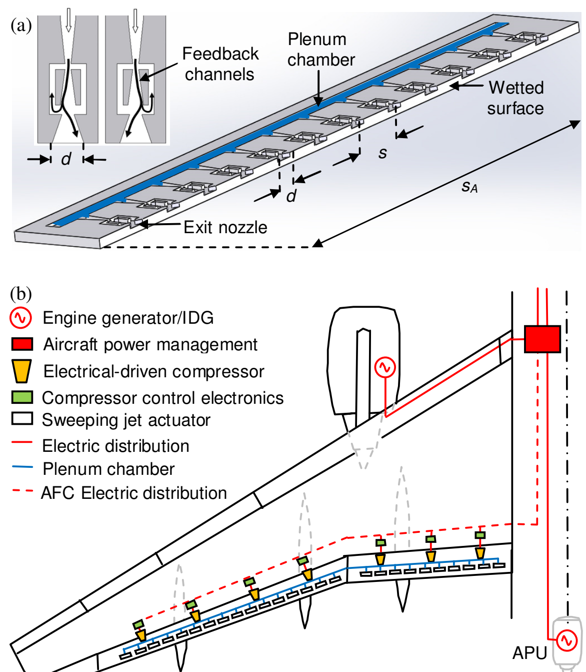

Figure 1: (a) main picture – oblique view of Advanced Fluidics SWJA array, and inset – side view of SJWA pair with feedback channels [1]; (b) AFC systems architecture

Where VR is the ratio of peak SWJA exit velocity, U_j, to free stream velocity, U_∞; Δ is the ratio of SWJA nozzle width, d, to local boundary layer height, δ; λ is the ratio of actuator spanwise spacing, s, to nozzle width; ρ is air density and s_A is the spanwise extent of the array. A summary of SWJA conditions at the TE flap is provided in Table 1.

Available power for the AFC system is limited to two engine integrated drive generators (IDGs), which deliver 90kW each and a back-up auxiliary power unit (APU). Power is conditioned by the power management system (details of which are given in [4]) before being distributed to electrically-driven compressors. The reference compressor has been developed for the cabin air pressurization system of the Solar Impulse aircraft [6], with a rated power of 150 W, mass flow rate 1 g/s and an efficiency of 74% (m_w=1.26 kg/kW). It also has an apt form factor; <47 mm depth with control electronics.

Table 1: SWJA conditions for full-span flap separation control

Input parameters		SWJA parameters		Output parameters (VR=1; λ=17; η_a=70%)	
U_∞	150 m/s	d	1 mm	n	945
δ	6 mm	Δ	0.16	$\dot{m}$	0.13 kg/s
ρ	1.2 kg/m^3	λ	8, 17, 25	n_c	130
VR	1, 2, 3	s_A	24 m	U_j	150 m/s
t	600 s	η_a	60, 70, 80%	Σm_w	2.64 kg/kW

Based on an AFC application with VR=1 and λ=17, the total SWJA mass flow rate requirement, $\dot{m}$=0.13 kg/s (Table 1). This requires 130 compressors (n_c), equivalent to 7 SWJAs per compressor. To examine SWJA parameter sensitivity on overall system power and mass, VR and λ are varied, as is SWJA nozzle efficiency, η_a, which is conservatively estimated to be 60-70% (S. Raghu, private communication, 2012).

RESULTS

The effects of λ and VR, on the overall AFC systems costs at η_a=70%, is shown in Fig. 2. Both the reduction of λ, i.e. increased concentration of SJWAs per unit span, and increase in VR lead to an increase in system mass (Fig. 2a), although this increase is more pronounced with VR due to the cubic relation of VR with SWJA fluid output power (2) and, ultimately, overall system mass (1). Preliminary wind tunnel tests indicate that a spacing between λ=17 and 25 is the optimal setting for effectiveness in flap separation control [3] and for VR=1 and 2, system costs appear feasible; system power requirements can be met by a single engine IDG for λ=17 and 25 (Fig. 2b). Conversely systems costs at VR=3 are prohibitively expensive, particularly at reduced λ. In addition, VR=3 (U_j=450 m/s; $M\approx$1.3) may be beyond the sonic operating capability of the SWJA. Wind tunnel tests of SWJAs for rudder separation control have shown however that a VR of at least 3 is required for effectiveness [7]. In this case, the system costs may be feasible at VR=3 compared with flap control, as both local U_∞ (typically less than 100 m/s) and s_A (max. 6 m, based on A320 vertical tail span) are notably smaller. The implications for flap control, if VR=3 is ultimately deemed a global requirement, is a reduced SWJA span application to either inboard or outboard flap.

Finally, the effects of SWJA nozzle efficiency, η_a, on the overall systems costs at λ=17 is shown in Fig. 3. A gradual reduction in systems costs is observed with increasing η_a, although its effect is less pronounced than λ and VR.

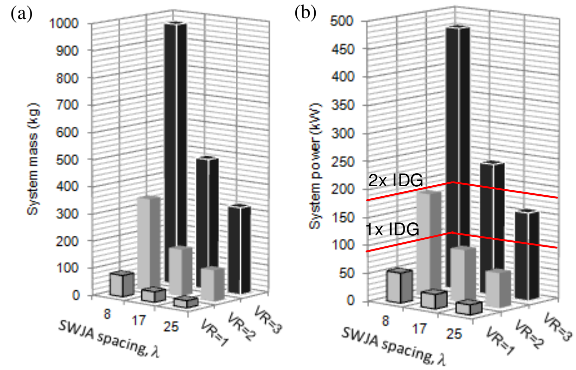

Figure 2: total AFC system (a) mass, and (b) power required as function of SWJA spanwise spacing, λ (η_a=70%)

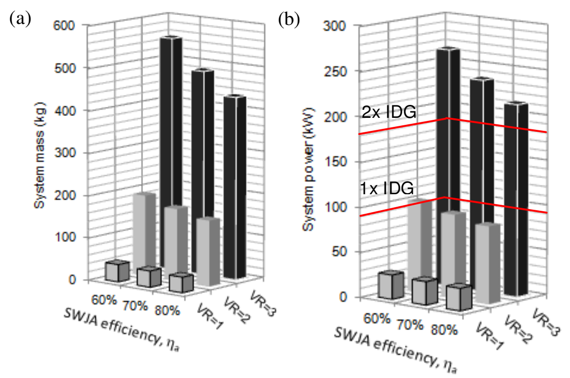

Figure 3: total AFC system (a) mass, and (b) power required as a function of SWJA nozzle efficiency, η_a (λ=17)

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