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Two-dimensional numerical modeling of interaction of micro-shock wave generated by nanosecond plasma actuators and transonic flow

M. Abdollahzadeh [a,*], J.C. Páscoa [a], P.J. Oliveira [b]

[a] Universidade da Beira Interior, Departamento de Engenharia Electromecanica, Centre for Aerospace Science and Tecnologies (CAST), R. Marques D Ávila e Bolama, 6201-001, Covilhã, Portugal

[b] Universidade da Beira Interior, Departamento de Engenharia Electromecanica, Centro Da Estudos de Fenomenos de Transporte (CEFT), R. Marques D Ávila e Bolama, 6201-001, Covilhã, Portugal

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ABSTRACT

The influence of nanosecond pulse-driven, surface-mounted dielectric barrier discharge (DBD) actuators on a transonic flow is studied numerically. An airfoil representing turbomachinery blades in transonic flow is considered as a test case. A two-dimensional fluid model of DBD is used to describe the plasma dynamics. The model couples fluid discharge equations with compressible Navier–Stokes equations. Simulations were conducted with an airfoil of NACA 3506 profile in a transonic condition of $M = 0.75$. When a nanosecond pulse voltage is used, with a rise and a decay time of the order of nanoseconds, a significant amount of energy is transferred in a short time from the plasma to the fluid, which leads to the formation of micro-shock waves and therefore to the modification of flow features. Moreover, a plasma energy deposition model is developed and presented by using the results of the plasma discharge model.

1. Introduction

For future huge airships, which are being designed to fly at very high altitude (as in the case of the MAAT project [1]), efficiency increase is a crucial subject. For such airships, any increase in propulsion system efficiency will lead to a decrease in energy consumption through a decrease in size, length and mechanical complexity of propulsion system, thus also lowering the initial investment. At the blades of a propulsion system, separation causes significant total pressure loss causing a reduction in overall efficiency.

The abilities of traditional flow control techniques are limited due to a strict localization and slow response of such systems.

Surface dielectric barrier discharges (SDBDs) can modify the boundary layer of a flow and have been studied as possible actuators for flow control. Their advantages include fast response, real-time control, low weight and no moving mechanical parts. In many applications, airflow control by DBD actuators is based on the generation of the ionic wind at the wall which adds momentum to the boundary layer. At low flow velocities, those actuators have proven to be effective for a wide range of applications [2,3]. At high flow velocities, however, the effect of the induced wall jet is almost negligible. In our previous study [4], the interaction between an AC-driven DBD actuator mounted on a NASA rotor 67 blade profile in transonic flow was

* Corresponding author. Tel.: +351 925467631; fax: +: 351 275329972.
E-mail address: mm.abdollahzadeh@yahoo.com (M. Abdollahzadeh).

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Nomenclature

C_p	Specific heat capacity (J kg^{-1} K^{-1})
n	Charge particle density (m^{-3})
t	Time (s)
r	Recombination coefficient (m^3 s^{-1})
D	Charged particle diffusion coefficient (m^2 s^{-1})
e	Electron charge (1.6×10^{-19} C)
$\vec{j}$	Total electric current (Am^{-2})
$\vec{J}$	Conduction current (Am^{-2})
$\vec{n}$	Unit normal vector
p	Pressure (N m^{-2})
k_B	Boltzmann constant (m^2 kg s^{-2} K^{-1})
m	Mass of particle (kg)
T	Temperature (K)
η_E	Fractional power deposited in electronic excitation
η_V	Fractional electron power deposited in vibrational excitation
η_{el-R}	Fractional electron power deposited in elastic and rotational excitation
σ_e	Electron conductivity (S m^{-1})
σ	Surface charge density (C m^2)
μ_i	Charged particle mobility (m^2 V^{-1} s^{-1})
μ	Fluid dynamic viscosity (Pa s)
ϕ	Electric potential (V)
ρ	Density (kg m^{-3})
$\vec{\Gamma}$	Charged particle flux (m^{-3} s^{-1})
ε	Permittivity (Fm^{-1})
δ	Delta function
γ	Secondary electron emission
E	Total specific energy (J kg^{-1})
$\vec{F}_{EHD}$	Electric force density (N m^{-3})
p_{th}	Electric power density (W m^{-3})
I	Unity tensor
R	Air specific gas constant (J kg^{-1} K^{-1})
$\vec{u}$	Velocity of gas flow (ms^{-1})
$\vec{E}$	Electric field vector, (kg.m.s^{-3}.A^{-1})

Greek symbols

α	Ionization coefficient, (m^{-1})
η	Attachment coefficient (m^{-1})
υ	Kinematics viscosity (N s m^{-2})
τ	Viscous stress tensor
τ_{VT}	Relaxation of time for vibrational excitation (s)
κ	Thermal conductivity (W m^{-1} K^{-1})
ξ	Effective fraction of energy deposition

Subscripts

e	Electron
p	Positive ion
n	Negative ion
s	Surface
d	Dielectric
0	Reference state

investigated and almost no noticeable effect of the actuator on the performance of the rotor was observed. Recently [5,6], it was shown that a DBD actuator driven by nanosecond (NS) pulse has a more significant impact on the transonic flow. It was found that in these types of DBD actuators, there is an overheating in the discharge region, which generates a compression wave emerging from the surface into the flow. In this case, the effective control of the flow implies an appreciable change