A Numerical Model of Plasma-Actuator Effects in Flow-Induced Noise Control

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Abstract—In this paper, a computational model was developed to model the potential of plasma actuators to reduce flow-induced noise. The model consisted of a viscous flow solver to compute the flow field and a Flowcs Williams and Hawkings acoustic solver to predict the far-field noise radiation. A velocity-inlet boundary condition was used to model the induced velocity effect of plasma actuators applied to the surface of a bluff body. A test case of the noise radiation from a cylinder in fluid flow was used to validate the model. A comparison between the numerical results and previous experimental results was made. The results confirmed the noise-reduction potential of plasma actuators for bluff-body noise control. Good agreement was made between the numerical and experimental results. It was concluded that the model could be a useful tool to predict the effect of plasma actuation applied to aerodynamic, acoustic, and optimization problems.

Index Terms—Aeroacoustics, atmospheric-pressure glow discharges, flow control.

I. INTRODUCTION

LOW-INDUCED noise generated during takeoff and approach-to-landing of civil aircraft can have a significant environmental impact on communities near airports. Various flow control methodologies are being investigated worldwide to minimize aerodynamically generated noise associated with aircraft components. Previous experiments have demonstrated that plasma actuators [1], operating under atmospheric-pressure air conditions, hold the potential to reduce flow-induced noise [2]–[4]. Compared to other actuators, the simplicity and absence of any mechanical moving parts make plasma actuators a promising option for flow/noise-control applications.

The history and principle of plasma actuators have been discussed in [5] and the references therein. Most recent applications include high-speed flow control using localized arc filament plasma actuators [6], surface impulse discharges [7], and glow discharges [8]; flat-plate boundary-layer flow control by nonthermal direct-current corona discharge [9]; airfoil separation control by glow-discharge plasma actuators [10]; and airfoil wake control by dielectric-barrier-discharge (DBD) plasma actuators [11]. Plasma actuators of DBD type were used in this paper for low-speed flow/noise control. For brevity, the name of plasma actuators applies to DBD plasma actuators in the rest of this paper.

The optimization of a flow-control system that adopts plasma actuators calls for a better understanding of the flow mechanisms under a plasma activation. Numerical modeling and simulation could be helpful to provide a physical insight, particularly for cases with complex geometries for which a flow measurement is difficult to be conducted. The computational models employed in the previous work fall in one of the following categories: kinetic models [12], continuum models [13], lumped-element models [14], and models based on the Navier–Stokes equations [15]. This paper presents a simple fluid model to study flow-control effects.

This paper is organized as follows. Section II introduces the fundamentals of the plasma actuators used in this paper. Section III briefly reviews the existing work on the modeling of plasma effects, specifically for aerodynamic applications. Section IV provides the computational details of the model used in this paper. Section V presents the results and discussion. Finally, Section VI presents the summary and conclusion.

II. PLASMA ACTUATORS

Fig. 1(a) shows that the electric power supply employed here is a switching circuit. Fig. 1(b) shows the structure of a plasma actuator that includes a pair of electrodes and a dielectric material to prevent electric arching. The voltage applied to the electrodes operates at a frequency of $f_p$. This plasma actuator consequently generates weakly ionized atmospheric plasma that consists of charged oxygen/nitrogen particles and electrons. The charged particles are coupled to an electric field, thus inducing a body force that affects the flow field that is local to the plasma actuator [1]. Through collisions between the charged and ambient particles, the plasma actuator acts as a jet along the actuator surface.

More specifically, a flow speed oscillating at the frequency of $f_p$ can be induced along the surface of the plasma actuator [16]. In a stationary flow field, the averaged induced jet speed is up to 8 m/s at $x_1 = 20$ mm and $y_1 = 2$ mm (see Fig. 2). This maximal averaged speed is reduced to 4.1 m/s at $x_1 = 30$ mm and $y_1 = 3.8$ mm. On the other hand, the speed oscillation at $f_p$ is on the order of 0.01 m/s [16]. As a result, the averaged-speed part is arguably regarded in this paper as a main mechanism for flow control.

In this paper, the peak-to-peak voltage applied to the plasma actuator is 25 kV. The power consumption per length of an electrode is 5 W/mm. In practical applications, these plasma...
actuators are only conducted in a relatively short duration of takeoff and approach to landing. Hence, this power consumption is acceptable for an aircraft system. The dielectric material is a silicon rubber with a dielectric constant of 4.5 ± 0.5 and a thickness of 1 mm. Fig. 2 shows that a glass material is a silicon rubber with a dielectric constant of 4.5. For atmospheric air, there were 17 species considered in [19], while 29 species were considered in [18], leading to a complex computation, even for the simplest 1-D case. Similarly, the kinetic model also includes complex governing equations for the simulation of plasma effects in atmospheric air. The assumption of a pure gas such as nitrogen or oxygen was therefore assumed in most works. In addition, the correctness of computation with either the continuum model or the kinetic model heavily depends on the right selection of the source terms (net creation rate for each species) in the governing equations, which is difficult to obtain.

In the lumped-element model, the plasma actuators are regarded as nonlinear electric impedance and solved with a simulation program with integrated-circuit emphasis (SPICE) [14]. As the governing equations are ordinary differential equations, this model can approximate electric properties quickly with commercial tools such as PSpice. However, the simulation of the interaction between the local atmospheric fluid and the plasma discharge is extremely challenging and has rarely been considered with the lumped-element model.

A model based on the Navier–Stokes equations has the ability to solve flow dynamics if a proper modeling of plasma effects is available. A simple approximation using an aerodynamic flow simulation collectively treated plasma effects as a body-force term [15]. The amplitude of the body force was assumed to be proportional to the externally applied voltage [15]. The voltage that is built up over the surface of the dielectric barrier was omitted in the model, which could lead to an overestimation of plasma effects in flow control. In this paper, a new model using a velocity-inlet condition to model the effect of plasma actuation was used. More specifically, plasma effects were approximated by an inlet flow whose direction and magnitude were specified along a segment of the boundary of a bluff body. Experiments were performed with various arrangements to suggest effective locations for plasma actuation over the cylinder surface. The noise reduction found in experiments was presumably achieved by modifying wake profiles with the externally induced speed from plasma actuation. The value of the inlet flow velocity was chosen to represent the mean speed produced by the plasma actuators. The main speed was measured by experiments. The existence of smaller time scales for plasma formation and velocity fluctuations of kilohertz frequency [16] should affect wake profiles little and were omitted in the model. A similar assumption can be found in the literature [23].

IV. COMPUTATIONAL DETAILS

A fluid model collectively treated plasma effects as a body-force term [15] in the Navier–Stokes equations. In this paper, a new fluid model using a velocity-inlet condition to directly model the effect of plasma actuation is presented. Plasma effects are approximated by an inlet flow whose direction and magnitude are specified along a segment of the boundary of a bluff body. The unsteady Reynolds-averaged Navier–Stokes (URANS) equations are solved numerically to model the effect
of plasma flow control applied to the flow around a bluff body. Compared to this previous model, the present one avoids solving electric equations. It is simple to understand and easy to use for fluid researchers. Only the collective effects of plasma actuation on local flow field can be simulated with this velocity-based model. A natural flow could also be interfered by small oscillations at the frequency of $f_p$ by nonlinear development, whose simulation, however, is beyond the current computational capability.

Fig. 4(a) shows that the velocity induced by plasma actuation is modeled by specifying a velocity-inlet boundary condition along a $5^\circ$ segment of the cylinder hard wall centered at two locations: $\varphi = 90^\circ$ and $\varphi = 270^\circ$, where $\varphi$ is measured anticlockwise from the positive $y$-axis. A no-slip boundary condition is specified along the remainder of the cylinder surface. The induced velocity is defined tangential to the boundary surface, and simulations are performed at a plasma-induced velocity of $U_i = 12$ m/s. Note that the induced velocity is assumed constant over the surface of the boundary condition and the same as the induced velocity at $x_1 = 10$ mm. The computational setup was configured as the experimental setup. It was also assumed that the curvature of a plasma-actuator surface affects the induced speed little.

Experiments are conducted to validate the model. Fig. 4(b) shows the experimental system that includes particle image velocimetry (PIV). The experiments are conducted on a cylinder model with a diameter of 100 mm and a length of 500 mm. It is presumed that the flow field distributes almost uniformly in the whole spanwise direction of the cylinder. The resolution for the PIV measurements is $\pm 0.1$ m/s. The PIV setup is omitted for conciseness. Related details can be found in [4].

The Spalart–Allmaras one-equation model [24] is adopted in the simulations to model the effect of turbulence. Although large-eddy simulation (LES) and detached-eddy simulation
(DES) are more desirable, URANS is capable of modeling the predominant flow features, and the associated low cost makes it a suitable alternative. The computational solver adopts second-order upwind spatial discretization and an implicit second-order time scheme with dual time stepping. The geometry is a 2-D cylinder of diameter $D = 0.1$ m. The computational domain consisted of an “O” grid with a resolution of $387 \times 290$. The first cell-wall distance is in the region of $y^+ = 1$ to ensure properly resolved boundary layers. The free-stream velocity is $U_\infty = 20$ m/s, leading to a Reynolds number of $Re_D = 1.4 \times 10^5$. It is also worthwhile mentioning that a thorough study for a suitable grid resolution is undertaken by comparing fluid results at grids with different resolutions. The nondimensional time step of the unsteady simulations was $\delta t = 0.005U_0/D$ corresponding to a sampling frequency of 40 kHz. The characteristic of cylinder flows is vortex shedding at a Strouhal number leading to a temporal resolution of approximately 1000 steps per shedding cycle.

V. Results

To verify the computational model presented here, the computational results for the flow field and far-field acoustics are compared to the corresponding experimental results. Details of the flow measurement system that includes PIV and an acoustic measurement system can be found in [4]. The experiments were conducted on a cylinder model with a diameter of 100 mm and a length of 500 mm. It is presumed that the flow field distributes almost uniformly in the whole spanwise direction of the cylinder. The resolution for the PIV measurements is $\pm 0.1$ m/s, while it is approximately $\pm 0.3$ dB for the acoustic measurements. A more detailed description of the setup can be found in the previous work [25] and is omitted here for conciseness.

The amplitude of velocity that is purely induced by plasma effects at $U_\infty = 0$ m/s is shown in Fig. 5. Fig. 5(a) is the experimental result for the velocity induced by plasma actuation at a peak-to-peak voltage of 25 kV with a sinusoid waveform. Fig. 5(b) shows the computational result with the inlet boundary condition set to $U_i = 12$ m/s. Both results show that the plasma actuator induces a similar velocity field along the negative $y$-axis.

Fig. 6 shows the computational results of the time-averaged $U$ velocity in the $y$-direction. To verify the computational model, the computational results are compared to the experimental results (see Fig. 7). Note that the plasma actuators work...
at a peak-to-peak voltage of 25 kV with a sinusoid waveform in the experiments. Both computational and experimental results show that the plasma actuators induce a similar velocity field along the y-axis. It is clear that, due to the plasma actuation along the surface of the cylinder in the upstream direction, the wake width (in the x-coordinate) is increased. The experimental results indicate an increase in the wake width of 18.5%. This compares to an increase of 16% in the computational results. In addition, Fig. 8 shows that the wake width of the experimental results in the x-coordinate is less than that of the computational results, which is attributed to the use of the URANS model. It is worth emphasizing that a 3-D LES or DES is more desirable to uncover the detailed physics. The related computational cost is, however, prohibitively expensive for the current case. As a result, the cheap URANS model was followed in this paper as a first trial to test the proposed plasma model in flow/noise-control cases.

To further verify the model, Fig. 9 shows the flow-induced far-field acoustic results that represent the collective effects from flow disturbances surrounding the bluff body. Differences in acoustic results between the on- and off-body integration surfaces were negligible, and so, only the on-body results are presented here. The value of the predicted sound pressure level (SPL) at an overhead position located 18 D away from the cylinder was computed. Fig. 9 shows that the flow-induced noise in the broadband frequency range was reduced by 2–3 dB when the modeled plasma actuation ($U_i = 12$ m/s) was applied. The SPL prediction indicates that the amplitude of the main peak at the Strouhal frequency, which relates to the vortex shedding, was only marginally affected. However, a dominant tonal
noise is rarely found in a practical aeroacoustic application. The control effects with the plasma actuators for broadband noise control should gain more interests for the area.

The SPL differences (SPL values with plasma actuation minus SPL values without plasma actuation) are compared in Fig. 10. A negative value denotes noise reduction due to plasma actuation. To verify the model, the computational results were compared to the experimental results. It can be seen that the computational result with the velocity-inlet condition prescribed to $U_i = 12$ m/s almost matches the experimental result at a frequency range between 20 and 2 kHz. However, local to the Strouhal frequency, the computational results show no noise reduction, while the experimental result indicates a 3-dB noise reduction. On the other hand, the simulation results deviate from the experimental results at high-frequency ranges beyond 2 kHz since the self-noise radiated from the plasma actuators (at a driving frequency of 3.8 kHz and its harmonics in the experiments) was not considered in the computational model.

The good agreement between the experimental and computational results in Figs. 9 and 10 suggests the effectiveness of the upstream-directed actuation in bluff-body noise control. A similar problem of cylinder tonal-noise control by the plasma actuators was studied previously [23]. Nevertheless, a downstream-directed plasma actuation was applied in that work to suppress the oscillations of a cylinder wake. As a result, the tonal noise at the Strouhal frequency has been attenuated almost completely for a cylinder case at $U_\infty < 10$ m/s. Instead of using the downstream-directed counterpart, our work suggests that the upstream-directed plasma actuation could reduce broadband noise, even at a high free-stream speed.

VI. SUMMARY

This paper has presented a simple computational model that employs the velocity-inlet boundary condition to model the plasma actuation applied on the surface of a bluff body. Compared to other models, the model is straightforward in its implementation and requires only low-cost computation. Both aerodynamic and acoustic computational results have been computed and compared to previous experimental results. The results have indicated good agreement, suggesting that the model is suitable to represent the main features of the noise-reduction mechanism. It is worth emphasizing that LES or DES is more desirable to uncover the detailed physics underneath noise reduction, particularly for cases at high Reynolds numbers. The related work by 3-D DES with the model of plasma actuation is ongoing.
In addition, a couple of conclusions can be drawn from the outcome. First, the computation suggests that the plasma actuation along the upstream direction is capable of reducing the flow-induced cavity noise by a bluff body. The model could be used to investigate plasma actuation in other directions, such as the downstream direction. Second, the present model is helpful to simulate the effect of plasma actuation in aerodynamic applications. The model can therefore be used in control effect prediction and control performance optimization.

**REFERENCES**


