Control of Dynamic Stall with Nanosecond-Pulsed Dielectric Barrier Discharge Plasma Actuators

PhD Research Abstract – Kristofer Meehan April 8th 2017

Helicopter rotors experience a wide range of flow conditions, ranging from subsonic and negative velocities on the retreating blade, to transonic conditions on the advancing blade. Of particular interest is the dynamic stall on the retreating blade, known as Retreating Blade Stall (RBS), characterized by high angles of attack and subsonic flow speeds. The RBS results from the retreating blade having a high angle of attack compared to the advancing blade, to minimize lift asymmetry on the aircraft due to the velocity disparity between the blades. If the RBS can be controlled, it is possible to control the aerodynamic behavior, reduce the acoustic signature, and reduce vibratory loads (A. Le Pape 2013). As an active control method, plasma actuation is well suited to dynamic flows such as that seen in helicopter rotors, when actuation is only periodically required. Plasma actuation for flow control has been an active area of research for over 50 years, and have been used for a variety of applications, including control of boundary layer separation, laminar-turbulent transition, shock wave shape, lift and drag, flow speed, and power extraction (Kalra et. al 2011, Moreau 2007, Roupassov et. al 2009, Leonov et. al 2010, Starikovskiy et. al 2011). While plasma actuation for boundary layer separation control has been thoroughly studied (Starikovskiy et. al 2011), only preliminary work has been done in unsteady flows (Meehan et. al 2017). For my PhD thesis, I would like to explore the capability of nanosecond pulsed Surface Dielectric Barrier Discharge plasma actuators to control dynamic stall in rotorcraft, improving the understanding of device physics and studying the relevant fluid dynamics.

The primary mechanisms of all plasma control are momentum or energy transfer to the flow; There are three major categories of actuators; electrostatic force, magnetohydrodynamic (MHD) force, and heat release. The former mechanisms, electrostatic and MHD forces, perform work on the flow by accelerating charged particles which collide with neutrals in the flow, imparting momentum to the bulk fluid (Likhanskii et. al 2008). The third mechanism, heat release, acts to locally perturb the temperature and density in the boundary layer. For aerospace applications, Surface Dielectric Barrier Discharge (SDBD) actuators are optimal actuator designs; they have high frequency bandwidth, can be surface flush-mounted, and actuate close to the surface within the boundary layer of the flow, giving them applicability to a wide range of flow conditions.

SDBD actuators have been shown to be effective at controlling stall for a wide range of flow conditions. Traditional AC frequency SDBD (AC-SDBD) actuators, which use the electrostatic force mechanism to accelerate the flow, have been shown to change the flow by several meters per second and manage boundary layer separation in main flows up to ~40 m/s. Nanosecond pulsed SDBD (ns-SDBD) actuators, which operate on the heat release mechanism, have been experimentally demonstrated to affect separated flows that are consistent with retreating blade flows (Meehan et. al 2016); for static conditions, in the range of Mach numbers ($0.03 \leq M \leq 0.75$) and Reynolds numbers ($10^4 \leq Re \leq 2\times10^6$) (Starkovskiy 2011). Thus, in this study we will focus on utilizing nanosecond pulsed actuation to control dynamic flows for rotorcraft.

In extending the ns-SDBD actuation to dynamic studies, the understanding of the flow and device physics must be expanded. For ns-SDBD actuators, heat release is accomplished by actuating with high reduced electric field (E/p), resulting in fast deposition of energy to the flow from the applied electric potential and localized density variation (Flitti et. al 2009 and Roupassov et. al 2009). By perturbing the shear layer between the separation bubble and main flow, vorticity is introduced to the flow, creating vortices that inject momentum into the separation bubble from the main flow. To develop an understanding of the ability of ns-SDBD to control dynamic stall, the controllable parameter space, and the applicable fluid dynamics, need to be studied. Variation of actuator placement, discharge frequency, actuation time, actuator voltage, and actuator geometry will be explored. Additionally, phase of actuation, pitching frequency, and Reynolds number values will be varied to enhance the applicability to rotorcraft applications.

The heat release mechanism has been experimentally shown to be ineffective when actuating in the separated region (Correale et. al 2011), however other methods, such as momentum transfer, could enhance overall actuation effectiveness. Electrostatic forces can be leveraged to aid in the reduction of the bubble size by imparting momentum to the boundary layer. Traditional AC-SDBDs have been shown to increase bulk velocities typically less than 10 meters per second (Starikovskiy et. al 2011), yet ns-SDBDs have been found to produce insignificant induced velocities. This has been shown to be due to a “backwards” breakdown, occurring after the actuation period, which imparts near equal and opposite momentum as the actuating pulse (Roupassov et. al 2009). This phenomenon results in zero net momentum transfer for traditional ns-SDBD devices. Potential methods of improvement have been suggested; one such method is to provide a preferential path through the surface for the charge after the actuation period (Starikovskiy 2013, 2014). Such a device is currently being made for experiments in collaboration with United Silicon Carbide, Inc. An alternate method suggests the elimination of the backwards ionization wave by introducing a phase delay in an array of electrodes (Meehan et. al 2016). Exploring alternate methods for ns-SDBD momentum transfer, and the effectiveness in dynamic stall reduction, will be integral to the study.

A thorough understanding of the resulting flow physics from plasma actuation is required. This includes understanding the vortex structure creation from heat release, the interaction of actuation induced velocity and density gradients, and the change in flow properties due to boundary layer actuation. In unsteady situations, the separation bubble is formed starting on the trailing edge of the airfoil. The ability to slow or affect the formation and propagation of the separation bubble over a wide velocity range is also of paramount interest. This includes the study of both shock-induced separation and subsonic separation control.

Due to the volatile nature of discharge regions, this project will depend heavily on optical diagnostics for the study of flow and plasma parameters. Intrusive measurements disturb the flow and the plasma greatly, necessitating the use of optical diagnostics. Flow parameters can be imaged with Schlieren to observe the flow field. Velocimetry measurements and vortex structure physics can be probed using Femtosecond Laser Electronic Excitation Tagging (Michael 2011). When necessary, downstream measurements of the velocity field can be made with non-conductive pitot probes.

In summary, ns-SDBD actuation shows great potential for active control of dynamic stall on helicopters blades. By utilizing a combination of heat release for boundary layer control and

momentum transfer with new SDBD geometries, pulsed plasma actuation will be applied to dynamic stall for the first time. A thorough study of the interaction of the actuation and resulting flow dynamics will be performed with a variety of diagnostics and over a large range of parameters. This study will improve the ability to control lift, drag, vibratory loadings, and aerodynamic behaviors of rotorcraft.

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