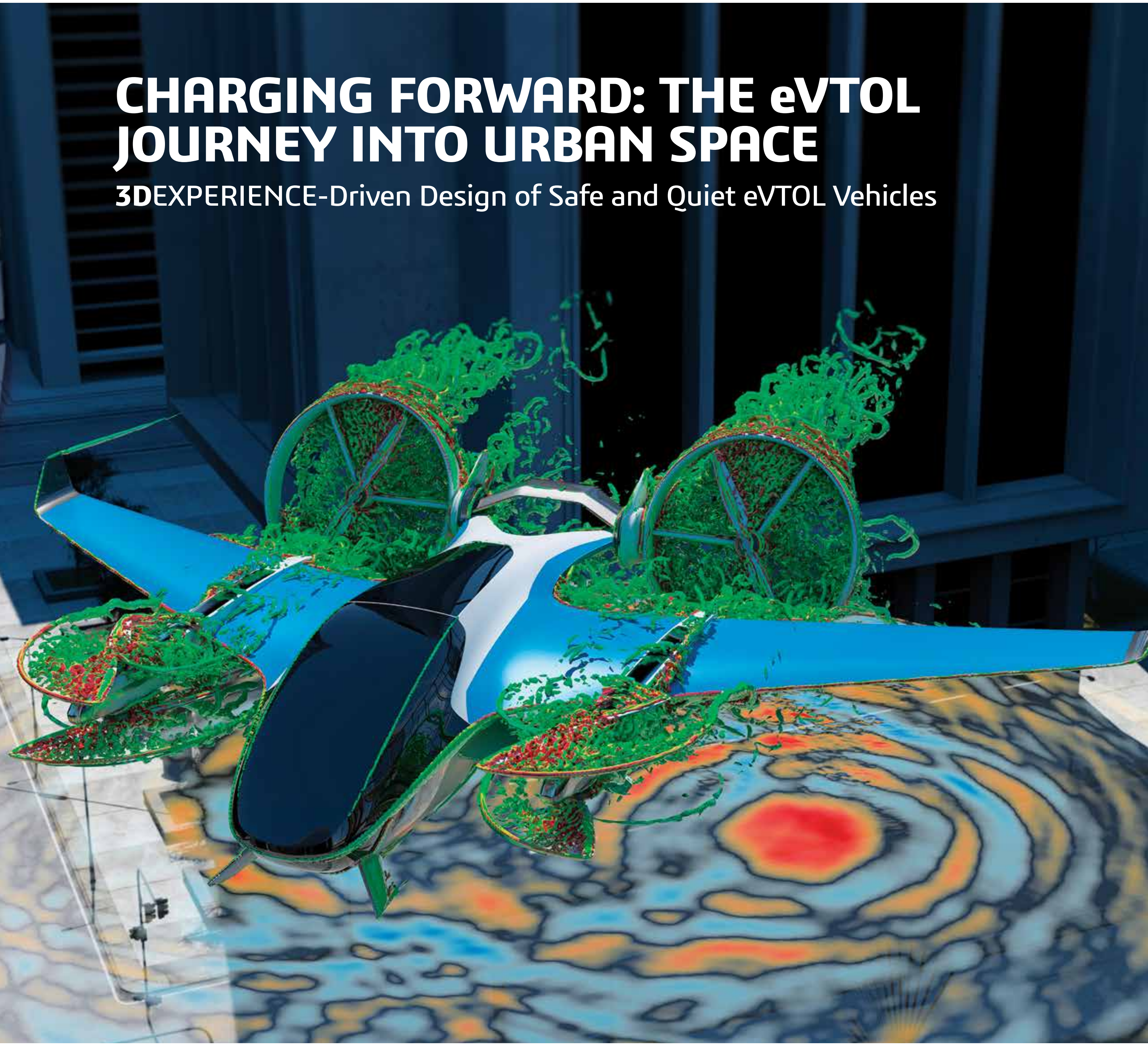

CHARGING FORWARD: THE eVTOL JOURNEY INTO URBAN SPACE

3DEXPERIENCE-Driven Design of Safe and Quiet eVTOL Vehicles

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CONTENTS

INTRODUCTION

Residents in both established and developing urban areas face a vexing problem: traffic congestion. Despite centuries of effort and billions of dollars' worth of public spending to alleviate over crowded roadways, the problem appears to be getting worse. With an increasing number of cars sharing the road, uncoordinated traffic management and limited parking, commuters struggle while emergency services face increasing delays. According to surveys, residents from London and Bangkok on average spend around 74 and 72 minutes respectively each day commuting to work [1] [2], equivalent to 14 whole days in a year wasted simply getting to and from work. This not only increases residents' fatigue but also contributes to carbon emissions and climate change. Innovators are applying several ways like mobile internet (MI), internet of things (IoT), autonomous vehicle (AV) technologies, immersive interfaces and so on to make travel time more productive. However, one innovation to improve urban mobility that is being taken increasingly seriously is personal air vehicles (PAV) and air taxis (AT). These electric and hybrid-electric powered vertical take-off and landing (eVTOL) vehicles have incredible promise in alleviating transportation congestion on the ground, operating through airspace.

eVTOL offers potential in urban mobility markets such as airport shuttles, on-demand air taxis and air ambulances. The closest equivalent technology which is used for point-to-point transportation is helicopters, but these are too noisy, inefficient, polluting, and expensive for mass use. Electric propulsion opens the VTOL aircraft design space by adding concepts such as distributed electric propulsion (DEP), as well as facilitating new approaches to wing-borne VTOL. Even though this is a new era in urban air mobility, there is already a scramble amongst well-known aerospace giants, as well as start-ups, to develop and evaluate the civil VTOL market, usually referred to as the Third Aerospace Revolution [3] .

Initiatives driving the air taxi concept include Uber Elevate, NASA UAM Grand Challenge and Kitty Hawk. Uber plans to offer a piloted on-demand air traffic service by 2023, and testing should begin in 2020. All of this has attracted the interest of several stakeholders, such as aircraft and car manufacturers, regulators, agencies, research institutions and academia. At present, the Vertical Flight Society has listed 155 different eVTOL vehicles that are under development. These designs include 55 vectored thrust aircraft, 17 lift-plus-cruise platforms, 34 wingless multicopters, 30 hover bikes and personal aerial devices and 7 electric rotorcrafts—with more appearing regularly[4]. Airport shuttle and air taxi markets are viable markets with a significant total available market value of $500B in an unconstrained scenario. Industry giants and start-up firms have capitalized on positive momentum for eVTOL vehicles, and have attracted more than $1 billion in investments.

The three most promising concepts for the battery-driven electric motor aircraft are the lift-plus-cruise configuration, tilt wing, and tilt rotor. With advancements in electric motors, batteries, computer modeling/simulation and composites designs across the globe, many eVTOL prototypes are being developed for urban commuting by Boeing, Airbus, Bell, Embraer, Pipistrel Aircraft, Lilium and others [5]. Flying is normally perceived as an expensive form of transportation that is infrequently used, and small aircraft and helicopters as too costly for urban mobility. For stakeholders involved, airport shuttle service is a feasible early market, and the air taxi is the mass market moving forward. But there are several challenges which need to be resolved to achieve wide adoption of eVTOL vehicles in the market. Key issues such as noise, operating efficiency, performance, reliability, safety, infrastructure development and affordability need to be addressed. There are significant challenges to make this urban air transportation market feasible.

ADOPTION CHALLENGES

This ambitious vision of urban air transport is achievable only with effective collaboration between vehicle designers, regulatory bodies, cities, communities and network operators. Before a VTOL craft can fly in low-level airspace, it will need to undergo scrutiny from aviation authorities such as the US Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA). Furthermore, there are challenges in determining which of the existing FAA certification standards to apply to VTOLs, and/or if the existing certifications may need amending. High technology companies and their CEOs may complain about the historic slow pace of regulations holding back their flying taxis, but recent accidents and costly groundings have demonstrated the value of aviation's tight safety rules.

The development of infrastructure to support an urban VTOL network is another challenge that needs attention from cities. The optimal location of vertiports (large VTOL stations with significant support infrastructure) and vertistops (more minor stations for quickly setting down and picking up passengers) is necessary for low-noise take-off and landing procedures. Repurposed parking garage roofs, existing helipads and shopping mall terraces are some of the proposed locations for boarding passengers. As of today, cities do not have the necessary take-off and landing sites and corporate authorities would need to perform 'what if' scenarios for urban and infrastructure planning, logistics, territorial management, and environmental adaption.

Societal barriers and public perception form another important obstacle in deploying eVTOLs in the market. Organizations like NASA and Airbus have performed surveys to understand perceptions about urban air mobility (UAM). The cost of transportation is always the primary consideration for travel, and people prefer piloted aircrafts to automated or remote piloted UAM aircraft. Safety and privacy are other concerns from the passenger's point of view [6]. This includes confidence in aircraft, which can be dependent upon whether or not the system is made by a well-known company, and privacy concerns related to people flying overhead having sight lines into homes and yards. Near-term technical challenges for companies who operate VTOLs or provide service in urban air mobility are Air Traffic Management (ATM), battery technology, vehicle performance, efficiency, and the economics involved. Distributed Electric Propulsion (DEP) affords fixed-wing aircrafts (with lifting and thrusting rotors) for efficient usage of batteries during cruise. DEP helps avoid the fundamental limitations of helicopter edgewise rotor flight, VTOLs with DEP can cover a target distance of 60 miles. Aerodynamic efficiency in cruise can be further enhanced through flight-conversion concepts such as tilt-rotors, retracting rotors and light-weighting of aircraft with the ultimate benefit of efficient battery usage [7].

One of the significant common apprehensions between manufacturers and the public that would affect VTOL acceptability is noise pollution. Noise from urban air mobility could pose a more notable barrier in the future as electric vehicles become more mainstream. VTOL developers need to keep noise mitigation as a top priority objective in order to obtain community acceptance. Electric propulsion will enable ultra-quiet designs, both in terms of engine noise and propulsion thrust noise, so it plays a critical role in achieving acceptable noise levels. Low-noise operation in urban areas and efficient usage of batteries for the targeted flight range can be further achieved with enabling technologies such variable speed open rotors and ducted fans, depending on the design of the VTOL, and the use of low-noise trajectories and maneuvers. A typical objective for noise level, set by Uber Elevate, is only 67 dB(A) at ground level from a VTOL at 250 ft. altitude [8].

In order to evaluate and optimize VTOLs noise levels, digital simulation/prototyping in a collaborative environment is recommended. This does not mean avoiding physical prototyping completely, but working with virtual models before committing to an expensive prototype avoids costly late stage redesigns due to missed targets after physical testing.

FASTER TIME TO MARKET

With increasing competition in the eVTOL sector, the first company to truly breakthrough into the market will have a significant advantage in terms of publicity, investment and brand recognition—their vehicle will be seen as the standard against which later offerings are judged. As such, the efficiency and connectivity of engineering tools used in the development of eVTOL concept vehicles is of critical importance.

Dassault Systèmes, the **3D**EXPERIENCE company, offers a wide range of capabilities within its Brand offerings, from life cycle management (ENOVIA) to design and system engineering (CATIA); manufacturing management (DELMIA);simulation in all physical domains (SIMULIA); and simulation of quantum, molecular, and mesoscales (BIOVIA). The **3D**EXPERIENCE platform integrates this portfolio of technologies, so that all engineers are working with one data source, in a concurrent and collaborative process.

A typical development cycle for an eVTOL vehicle might be as follows: requirements gathering, planning, initial conceptual designs, detailed designs, prototyping, testing, preparing certification documents, and finally… manufacturing. Digital data is generated during each phase of this cycle, which must be managed, shared, and properly archived.

Once requirements (such as number of seats, maximum flight range, piloted or autonomous, Maximum Take-off Weight (MTOW), etc.) are determined, the design engineer begins with preliminary dimensioning of lifting surfaces, propulsion units (e.g. rotor, shrouded rotor) or reference propulsion units. The challenge here would be to start designing the vehicle configuration and a baseline blade definition, in order to define a preliminary low-noise propulsion system through a low-fidelity optimization at component level. The next objective for the preliminary design team is to determine the RPM of lifting thrust in the hover condition and decide on thrust/power in cruise, to achieve maximum flight range and maximum aerodynamic efficiency. This requires a trade-off between performance parameters and noise. In the next step, the flight mechanics engineer can begin to understand the preliminary propulsion unit performance characteristics and aerodynamic polars. For eVTOL systems, it is important to design the vehicle configuration around flight procedures of minimum noise during take-off/ landing conversion, minimum battery consumption in cruise, and reduced load factor for weight constraints. Preliminary airframe geometry can be built to determine power regimes in the flight envelope.

For this initial conceptual design phase, preliminary design and flight mechanics engineers require parametric geometry models to gauge feasibility of multiple designs. CATIA enables engineers to create any type of 3D assembly, with high end parametric CAD capabilities. CATIA on the **3D**EXPERIENCE platform fully integrates the cross-discipline modeling, verification and business process support needed for developing complex eVTOL vehicles. In addition to defining lifting surfaces and propulsion units, engineers can explore topology optimization or structure morphogenesis in various members of the airframe. Design and simulation tools from CATIA and SIMULIA provide design space exploration using non-parametric as well as parametric optimization. Multi-body dynamic simulation plays a crucial role in defining propulsion unit performance characteristics, and these capabilities are also available with the SIMULIA Simpack tool. Both low and high fidelity CFD analyses can be performed in this preliminary design stage to predict the noise footprint in conversion maneuvers and trajectories.

In the detailed design stage, propulsion and applied aerodynamic engineers can start looking into system optimization. To achieve maximum propulsion and aerodynamic efficiency, it is important to carry out a detailed optimization. Different parts of the eVTOL vehicle will undergo elastic deformation during operation, and this must be considered for further refinement of the vehicle configuration at this stage. Engineers can perform further optimization of the uninstalled propulsion units in hover conditions and design low noise devices to alleviate loads during conversion. Blade-Vortex Interaction (BVI) phenomena are likely with multi-rotor configurations and low noise procedures can achieve minimum BVI conditions. All of these system optimizations require high fidelity CFD analysis to understand the effect of different geometrical features on noise levels. SIMULIA PowerFLOW and XFlow tools can be used to perform aerodynamic and aeroacoustic optimization, and in detailing the design of control surfaces with optimal loading respectively .

In the final stage, flight mechanics and aerodynamics engineers will aim to design the quietest conversion trajectory constrained by g-factors. Once the vehicle configuration is defined, high-fidelity CFD computations of the complete configuration, along with installed propulsion units, can help to generate a noise database for trajectory optimization. SIMULIA tools can help in both system optimization and conversion aeromechanics and aeroacoustics of the detailed design, to achieve optimum airframe design and minimum noise impact. The tradeoff between minimum load factors and footprint noise in an aeromechanical trim loop can be made using Simpack for dynamic trimming coupled with a full-aircraft aero database. Understanding the challenges related to eVTOL concept feasibility and the methodology for digital prototyping, we can now dive deeper into how to improve structural, dynamic, aerodynamic and aeroacoustic performance of these aircraft.

OVERCOMING SOCIETAL AND LEGAL BARRIERS

Overcoming societal barriers and positive public perception are key to successfully deploying eVTOLs into the market. The safety of eVTOLs is of primary importance both for the public, as well as certification authorities. SIMULIA's suite of simulation tools has been used extensively in the aerospace industry for several decades to address these concerns, and is now being leveraged for this emerging technology. Noise is another major societal barrier affecting the adoption of eVTOLs, and only high-accuracy, transient CFD solutions are able to predict full vehicle noise levels. These strict noise requirements, as well as societal pressures to move towards clean power transportation options, have driven this industry to significantly advance battery technology, and SIMULIA multi-scale simulations can help to address many engineering challenges here as well.

Safety concerns are typically related to how an aircraft will withstand damage against potentially catastrophic events. As eVTOL vehicles are designed to fly at altitudes of 500-5000 ft, bird strikes and hail can lead to serious structural damage. All forward facing components, such as the windshield, window frame, radome, fuselage skin, as well as the leading edges of the wings need to provide a certain level of impact resistance. Numerical methods available with SIMULIA Abaqus/Explicit can simulate bird impact on the different vehicle components. Langrangian, Eulerian, and meshless particle modeling (SPH) methods are all available and widely used, each having specific advantages for different applications. SIMULIA simulation results have shown a strong agreement with experimental results in published literature both for bird and hail impacts [9]. Though these are not the only safety concerns for eVTOL vehicles, engineers can use these impact simulation methodologies to design vehicles for safety against a wide variety of phenomena (including Barely Visible Impact Damage or BVID).

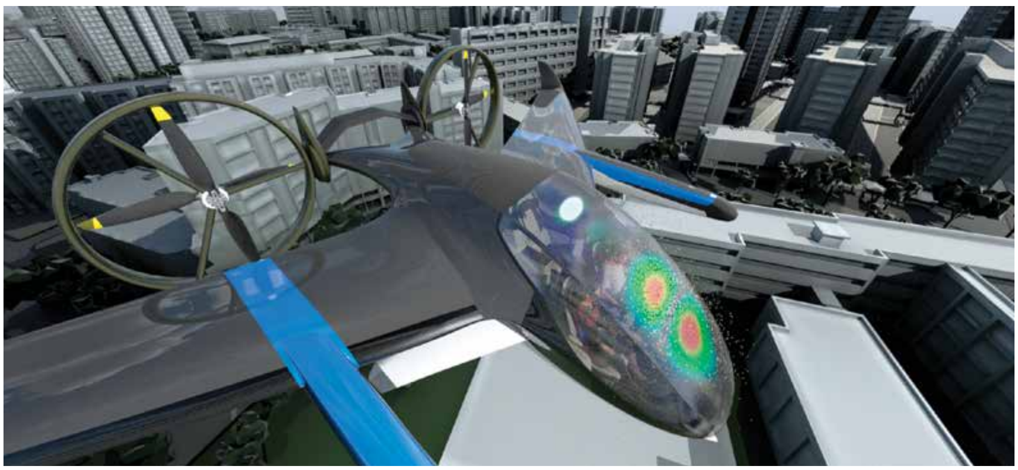

Figure 1: Windshield bird strike impact

Another basic safety requirement for eVTOL vehicles is continued safe operation when exposed to different electromagnetic environmental effects (E3), such as lightning. An aircraft is vulnerable to lightning strike when it passes through charged regions of clouds during a thunderstorm. The aircraft may attract lightning, due to its electrical conductivity, and become part of the lightning path. It is essential that communications and flight control systems are not damaged and remain operational. Lightning strike testing on prototypes of scale models is incredibly expensive and time-consuming. Also, scaled models for electromagnetics have low fidelity compared to full size aircraft and the results of such tests must be treated with care [10]. As an alternative to laboratory tests, CST Studio Suite® from SIMULIA can perform electromagnetic (EM) simulations to analyze the susceptibility of aircraft to lightning and other electromagnetic environmental effects.

Lightning analysis starts with an electrostatic analysis of the fields around the aircraft to determine where the field concentrates, and this corresponds to the most probable lightning attachment points. This kind of analysis is often referred to as attachment zoning. When lightning attaches to the aircraft, a channel is formed, and a transient return stroke current will flow with a huge peak current of some 200 thousand amps. The SIMULIA transient EM simulation technology enables the return-stroke to be simulated directly in the time-domain. The aircraft model is connected into a virtual lightning channel and the current distribution is simulated over the entire aircraft and cable system. The effect of using different airframe materials, such as composites can be assessed. A metal airframe tends to keep the lightning current on the outside of the aircraft, whereas composites allow current to diffuse through the skin to the inside, potentially coupling to cables systems. Modeling lightning strike is critical to ensure that electronics systems are sufficiently shielded and protected, and this workflow is shown in Figure 2.

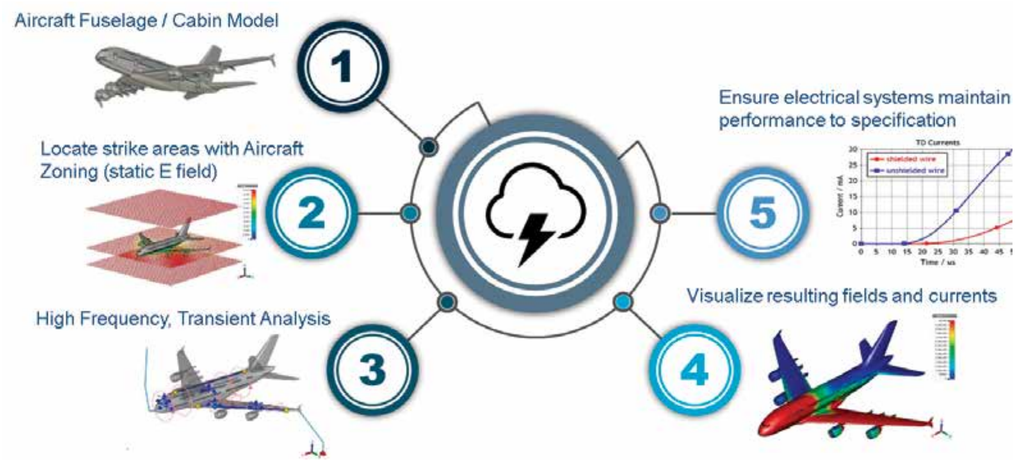

Figure 2: Typical lightning strike analysis

In CST Studio Suite, all three steps: pre-processing, EM simulation and post-processing can be performed in a common user interface for virtual EM eVTOL testing. Depending on the specific case, either high-frequency or low-frequency formulations can be used. Field probes and current monitors are essential to calculate the progression of the lightning strike at different points on the aircraft [11]. Virtual electromagnetic aircraft testing complements the testing of physical prototypes in the aircraft development and certification process.

Another societal or legal challenge is the noise level generated by eVTOL vehicles, as they will operate directly overhead, and in close proximity to urban spaces. Dassault Systèmes has designed a concept eVTOL vehicle, as shown in Figure 3 which consists of eight, 1.17m radius propellers which contra-rotate to maintain balance and stability. The rear propellers are shrouded and tilt-able during vertical to horizontal flight conversion. The total wing span is 15m wide, while the full fuselage is approximately 7m long.

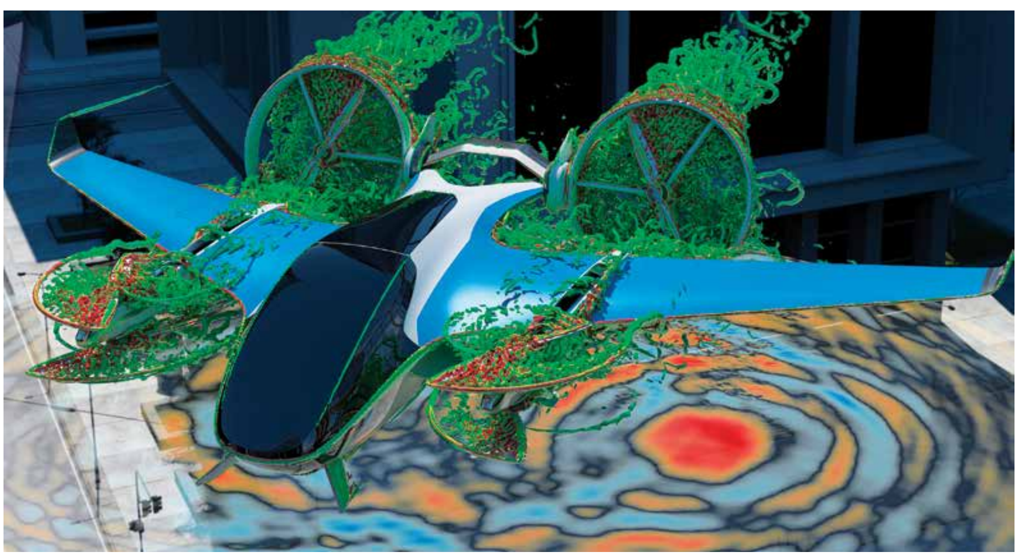

Figure 3: Dassault Systèmes eVTOL concept vehicle

The noise levels for this vehicle are predicted using the high-fidelity SIMULIA PowerFLOW CFD solver, which is based on the Lattice-Boltzmann-based technology [7]. In this proof-of-concept, an approach is presented for trajectory optimization using noise hemisphere database (NHD) noise extrapolation, where a full detailed and exact representation of the model is simulated using variable resolution layers (VRs). The flight envelope is covered by considering different combinations of flight Mach number, angle of attack, tilt angle of the rear rotors and rotational speed of the four rotors. The Ffowcs-Williams- Hawkings analogy is used to compute the narrow-band noise spectra on a hemi-sphere centered around the vehicle and stored in the noise hemisphere database (NHD). The trimmed flight trajectory is defined as a time-sequence of waypoints, pitch, yaw, roll, tilt angle and rotor RPM. Each point on the trajectory defines a quasi-static trimmed condition, the weight and the aerodynamic drag being balanced by the lift and thrust generated by the wings and the rotors. After running the NHD-footprint workflow, a noise prediction on a rectangular carpet is obtained. Representation of the evolution of the noise map in time in terms of overall sound pressure level (OASPL) is shown in Figure 4, along one of the 3 trajectory paths studied.

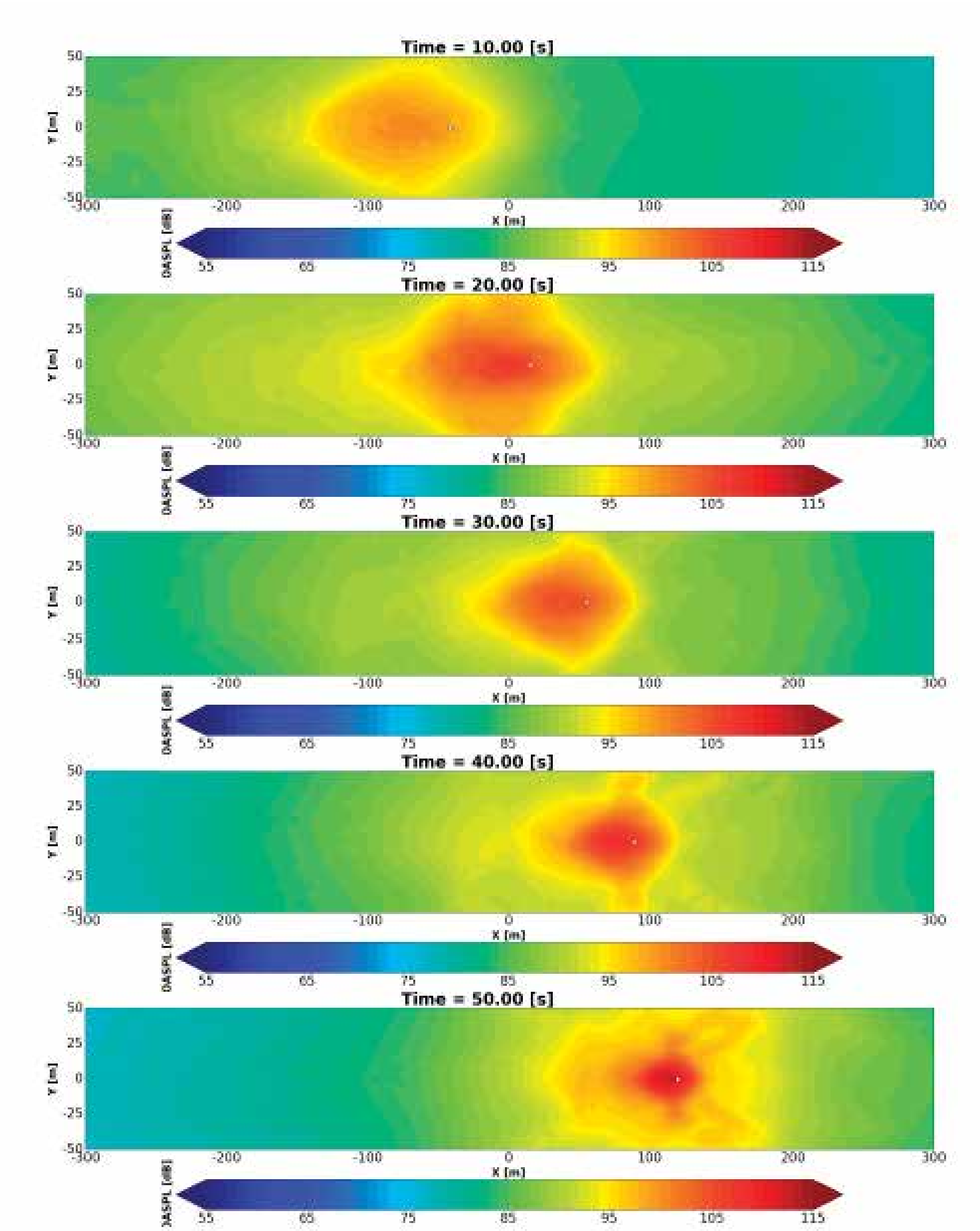

Figure 4: OASPL snapshots for five time instances along a path

The three considered trajectories reveal large variations in the on-ground noise levels, so it is interesting to study some isolated cases from the NHD in more detail. Some of the observed noise increases are potentially correlated to; (i) the rotor speed at the beginning of the conversion maneuver, and (ii) to the rear rotor tilt angle after the vehicle pass-by over a given microphone. The following Figure 5 shows the influence of the rear rotor tilt angle for two descending flight cases with the same flight speed, glide angle and rotor RPM.

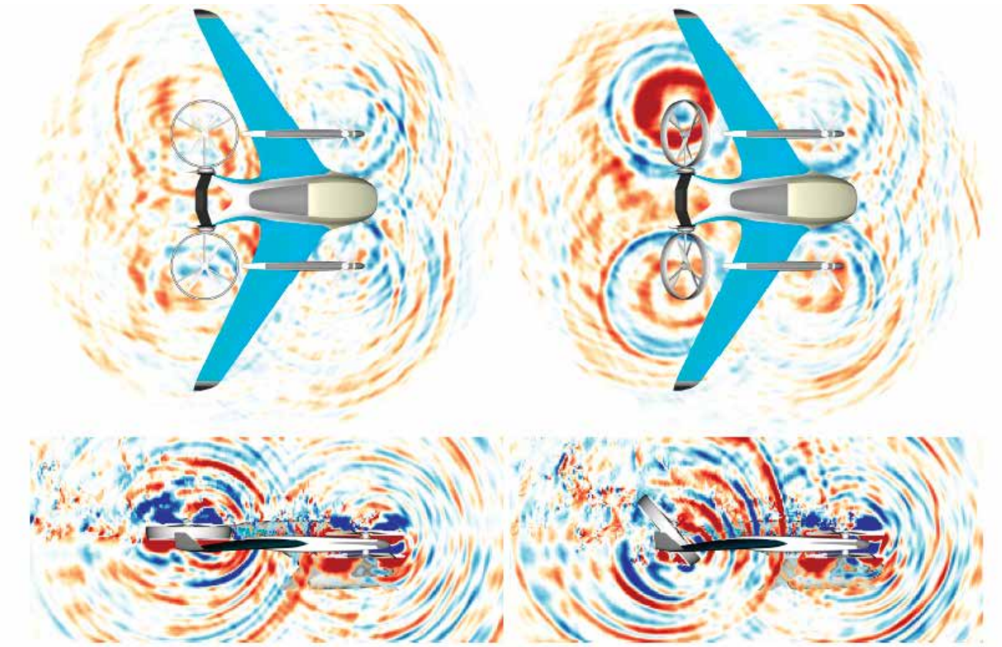

Figure 5: Instantaneous dilatation field for two different cases of rotor tilt angle

Electric or hybrid electric power is key to reducing aircraft noise, as well as satisfying public demand for clean energy. Battery technology is a primary challenge for eVTOL vehicles, in terms of achieving sufficiently high energy density while minimizing weight. Additional concerns regarding thermal management, battery safety and reliability, how the battery ages, and how it ultimately fails must be addressed for the adoption of eVTOL vehicles. To fully optimize battery technology, we need to consider battery behavior across all scales, beginning with molecular 3D modeling solutions from BIOVIA, as shown in Figure 6.

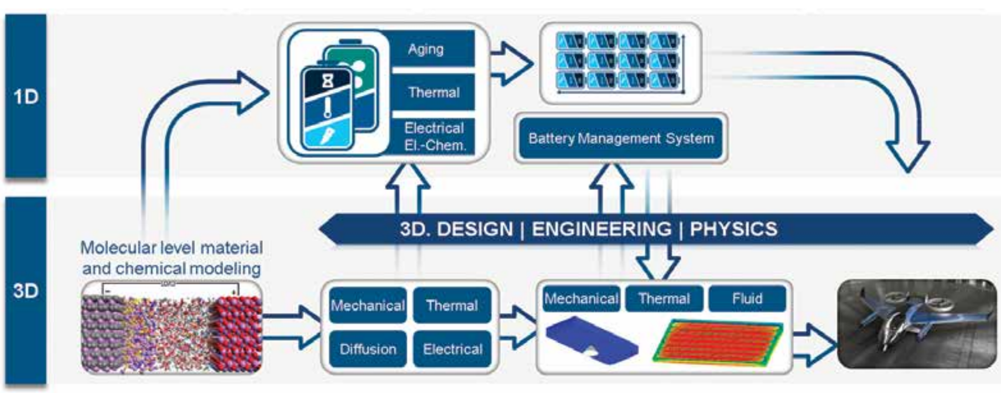

Figure 6: Battery engineering from chemistry to systems

These chemistry modeling capabilities allow for the testing of different electrolyte formulations, predicting dendrite formation on lithium metal anodes, cathode failure characterization, and solid electrolyte interphase (SEI) characterization, leading to optimally designed battery materials for aging. These molecular behaviors can then be used to inform the next level of simulation, typically looking at a 1D representation of how an entire module of cells behaves. In this system-level representation, the aging, thermal, and electrical behaviors of each cell are modeled with CATIA systems by a network of governing equations, that are combined to understand how an entire module of cells behaves.

With the molecular level modeling characteristics, mechanical, thermal, diffusion, and electric behaviors of the individual cell can then be simulated in 3D. Digital prototypes built on the **3D**EXPERIENCE platform give insights into thermo-electric losses from battery cells. Structural integrity of the battery cell is assessed using virtual compression, 3-point bending and impact tests. When a battery is charged or discharged, the core material expands during lithiation and delithiation, resulting in a change in thickness of the anode and cathode. The resulting internal stress influences the mechanical response of the cell. Simulation offers insight about radial expansion within the cell and guides for indentation tests.

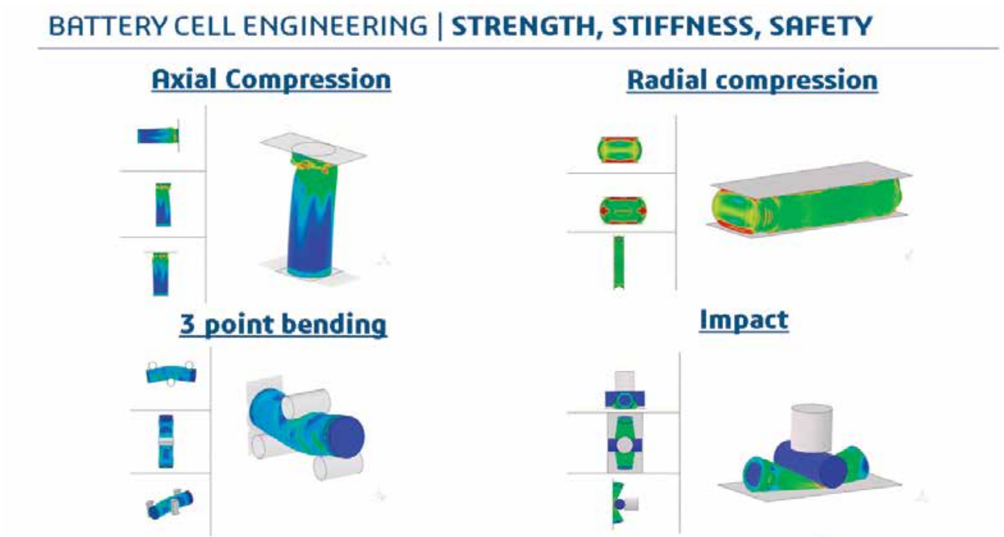

Figure 7: Structural simulations on battery cell

With 3D understanding of individual cell behavior, full battery modules can then be simulated, to improve strength, stiffness, and safety. As shown in Figure 8, drop test simulations, which mimic abuse during assembly or maintenance, provide an assessment of impact resistance of the battery module. Efficiency of thermal management strategies can also be determined. There are many other tests that can be performed using Abaqus, including expansion due to state of charge (SOC), ultrasonic welding analysis, short circuit analysis due to deformation of anode and cathode, and heat generation due to discharging. All of these workflows provide insights to optimize battery engineering.

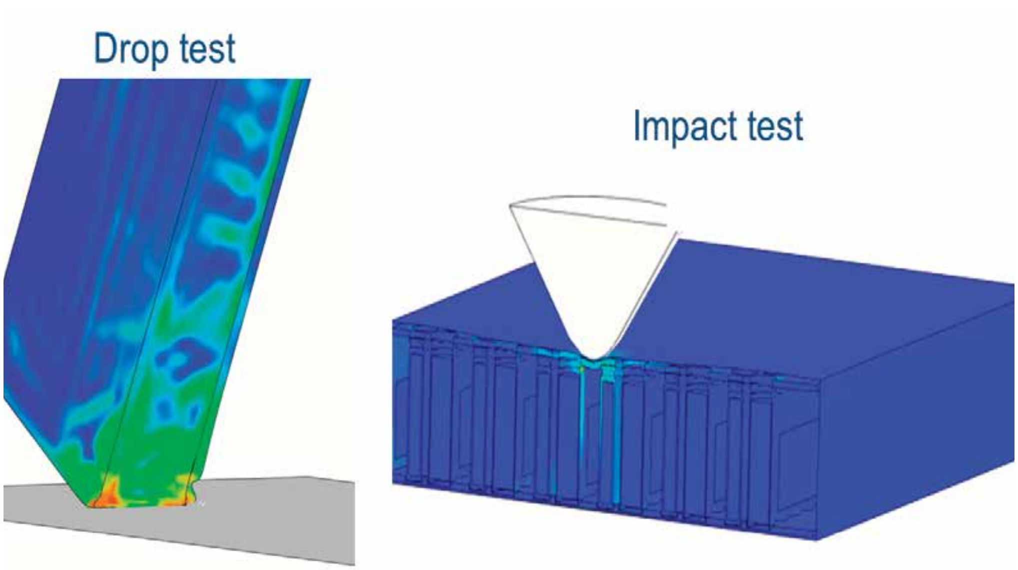

Figure 8: Structural simulation tests on battery module

3DEXPERIENCE PLATFORM APPROACH TO REINVENT THE SKY

Electric vertical take-off and landing (eVTOL) design and development is in an exciting time of technical improvements. Both OEMs and suppliers are leading advancements in sensors, chips, batteries, and materials to provide the best experience for final customers. In order to develop the next market-leading aircraft, manufacturers need to ensure that their design teams are not working in silos, rather coordinating and leveraging the input of many suppliers to maximize the value of their expertise. Dassault Systèmes is committed to supporting start-up and innovative

OEMs in developing this new mobility experience. The **3D**EXPERIENCE platform provides the ability to connect teams together, manage information, and promote collaboration—a fundamental requirement for success.

The **3D**EXPERIENCE integration of high-end CAD functionality from CATIA, and proven simulation technology from SIMULIA, has resulted in a shift in design paradigm. Instead of simply checking if a design meets requirements, we can now use technology to find the design that best meets the requirements, resulting in highly optimized lightweight structures. Lightweight structures are key for eVTOL vehicle design, to maximize range. Advances in additive manufacturing (AM) are giving freedom to designers to dream, innovate, and realize their lightweight organic concepts. Dassault Systèmes offers a cutting-edge technology solution in this area, which is being leveraged to shorten the design cycle for lightweight parts using topology optimization. Functional generative design on the **3D**EXPERIENCE platform is backed by the well-known Tosca solver and provides a topology optimization technique that identifies and removes areas of a design space not contributing to the stiffness of the part. This determines an optimum material distribution in a defined design area, while accounting for existing constraints to the design space such as boundary conditions, connections and pre-tensions, loads, and frozen regions. Validations can be performed on the optimized design, and an ideal design variant can be confidently selected using trade-off study tools. One of the main challenges of using optimization in design is the difficulty in reconstructing a native CAD representation from simulation results. The functional generative design application has a one-click functionality to convert topology optimization results into CAD, with additional CAD reconstruction tools available, making simulation augmented design an intuitive and simple process.

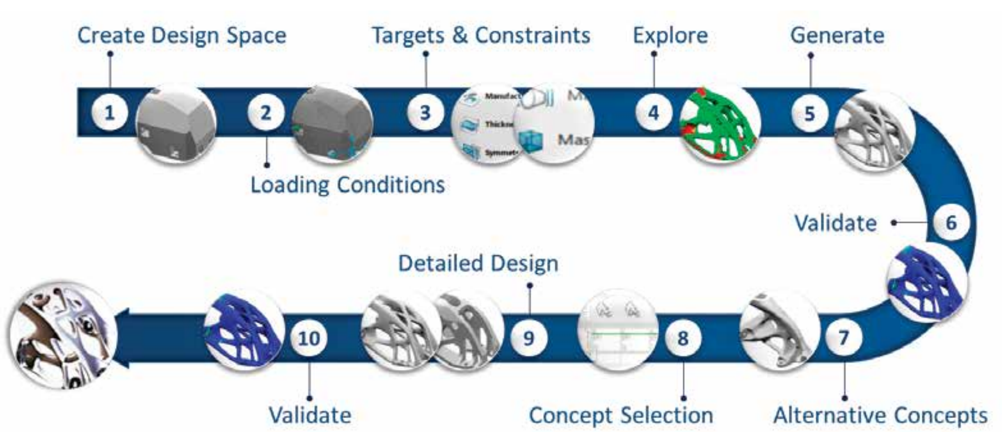

Figure 9: Functional generative design workflow

A CATIA and SIMULIA integrated solution can also provide engineering efficiencies for proven aerospace technologies, such as the use of composites. Composite materials are predominantly used for aeronautic primary structures such as wing components or fuselage panels, and this is also applicable for eVTOL vehicles. SIMULIA has been the leader in composites simulation for the aerospace industry for more than a decade, since Boeing selected Abaqus in 2004 for commercializing the then state-of-the-art virtual crack closure technique (VCCT) composites simulation technology [12]. With the increased use of composites, the VCCT technique has become status quo in mitigating delamination concerns. Integrated CAD and simulation technologies in **3D**EXPERIENCE allows for seamless translation of the layup definition associated with CAD to be used for any downstream simulation model, with automatic updates to layup section properties when design changes occur.

In addition to CAD integration, the **3D**EXPERIENCE platform also enables multi-disciplinary simulation, such as fluid-structure interaction. The efficient use of batteries for a targeted flight range is dependent on the aerodynamic efficiency of the eVTOL vehicle in cruise conditions; however, maneuverability is also a concern for landing and take-off in small spaces, such as rooftop vertiports. SIMULIA XFlow offers numerical simulation of complex fluid-structure interaction, which is required to predict maneuvering of aircraft vehicles [13]. Maneuverability often involves the presence of moving parts, such as the deflection of the elevators, the ailerons, the elevens, tilt-rotor or retracting rotors. Wind tunnel and flight tests data are often not available until late in the overall development process— resulting in costly late stage re-designs. In this context, XFlow is considered as a promising tool to estimate aerodynamic data for flight maneuvers in the early design stages.

The XFlow Lattice Boltzmann particle-based approach is capable of determining dynamic stability. eVTOL test maneuvers such as pitch capture, Dutch roll, stall, and spin can be evaluated with virtual prototyping, as shown in Figure 10. XFlow offers the potential to reliably evaluate the flight handling characteristics of any eVTOL configuration at the conceptual design stage, and can complement wind tunnel results with dynamic stability data. Indeed, because of the lower altitude at which eVTOL vehicles fly, they are more likely to face turbulent flow conditions and strong wind velocity gradients due to the proximity of urban buildings and the ground. This directly affects the eVTOL stability and makes its maneuvering more challenging in such adverse conditions near urban areas. Due to the capability of XFlow to simulate rigid body dynamics behaviors up to 6 degrees of freedom, it is possible to simulate different flight scenarios and wind perturbations in order to analyze the dynamic response of the eVTOL and reduce the time to recover its stable position.

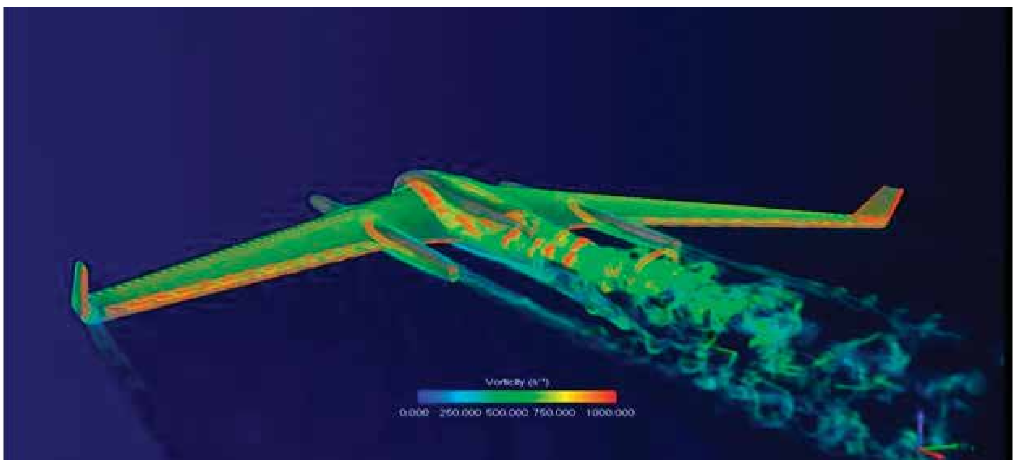

Figure 10: eVTOL dynamic response to pitch oscillations

Multi-disciplinary simulation is also required for the propeller design process. Depending on the propulsion configuration (tiltrotor, multicopter, lift-plus-cruise), different types of simulation of a multitude of load cases can be necessary. SIMULIA Simpack is a comprehensive tool that allows for multibody simulation, in addition to flexible components with complex kinematics and large relative motion. Simpack is provided with an extensive library for multibody system elements. Various abstraction levels for flexible bodies can be used, ranging from linear flexible behavior to geometrically nonlinear flexible bodies up to co-simulation with arbitrary nonlinear finite element models, to control solution time and fidelity.

Under operation, eVTOL rotor blades can undergo a significant amount of distortion, and this should be accounted for during the blade design phase. Reduced order modeling (ROM) technologies are essential for multibody simulation to account for nonlinear effects in fluid-structure coupling in multibody system (MBS) simulation. Because of its shape, rotor blades can be abstracted as beam structures, and Simpack supports Composite Beam technology where three-dimensional (3D) prismatic continuum can be approximated as beams. CATIA on the **3D**EXPERIENCE platform can easily be used to design a 3D CAD model of the rotor blade, assign material properties, and convert it into a flexible beam model. Finite element analyses can be carried out for each cross-section mesh of the beam, and based on the resulting beam element's material matrices, a complete geometrically nonlinear beam representation of the rotor blade can be generated. This representation of the rotor blades can then be integrated into a full multibody system representation of the entire eVTOL vehicle. The full vehicle model can then be coupled with aerodynamics or aeromechanics simulation to predict dynamic effects of the vehicle and also within the blades, such as propeller moment, Coriolis effects due to bending of the blades, and centrifugal stiffening.

A polar-based approach can be used to calculate the forces and moments generated by the horizontal and vertical tail plane, as well as the drag of the fuselage. These simulations can determine the required pilot controls, such as collective control angle, longitudinal and lateral control angles to maintain a steady forward flight or hovering. Due to the high abstraction level of the simulation model, a large number of maneuver simulations based on stick movement can be carried out to validate and improve designs. The results can give a better idea about flight controls in the design phase itself.

The greatest operational barrier to deploying an eVTOL fleet in cities is a lack of sufficient locations to place landing spots. As a starting point in providing initial limited VTOL service, heliports, which are already present in cities, can be used as vertiports, provided that these are in the right locations and are readily accessible from street level. However, in the long term, placement of vertiports should be easily accessible within city centers or downtown cores, and this introduces significant challenges for city administrative authorities. **3D**EXPERIENCity® powered by the **3D**EXPERIENCE platform offers game changing innovation for managing territorial complexity. It links all players including city mayors, transportation planning managers, utility network providers, city councils, regional and urban planning departments, regulatory agencies, architects, engineers, and general contractors in a collaborative working environment—enabling access to single source of truth data repositories [14]. **3D**EXPERIENCity leverages the power of Dassault Systèmes' **3D**EXPERIENCE platform to bring together a wide range of territorial data with industry-leading analytical, modeling, simulation and lifecycle management capabilities. For example, Virtual Singapore **3D**EXPERIENCity supports the work of governmental leaders, citizens, businesses, and the research community to collaborate in building a smart, sustainable, resilient, and prosperous Singapore.

eVTOL operations in urban areas are challenged by the need to reduce noise generation. It will be necessary to perform noise impact analyses in urban areas to develop low-noise take-off and landing procedures and to decide the optimal location of vertiports and the optimal orientation of the flight corridors. To address this, acoustic sources can be predicted by using the high-fidelity CFD solver, SIMULIA PowerFLOW. Acoustic propagation in quiescent air is computed directly by performing transient CFD simulations in a domain encompassing the urban assembly and the vehicle. Figure 11 shows an instantaneous view of the acoustic field filtered around the eVTOL vehicle. The complex wave pattern is the result of multiple reflections on the surfaces of the buildings and multiple edge diffractions.

Figure 11: Sound field on the building surfaces

With dozens of startups working to make eVTOL technology a reality, IT infrastructure requirements are a key factor in whether or not advanced simulation technologies can be leveraged for vehicle development. Physics simulation and optimization are examples where specialized high-performance computing (HPC) is required in order to solve complex problems and complete them in a timely manner. The required architecture typically comprises multiple nodes (individual computers in a cluster), multiple computing cores per node, large shared memory, fast storage and high speed, low-latency interconnects. The cost and configuration options can be quite broad. In addition to the raw hardware cost of HPC systems, there are many associated peripheral costs, as shown in Figure 12.

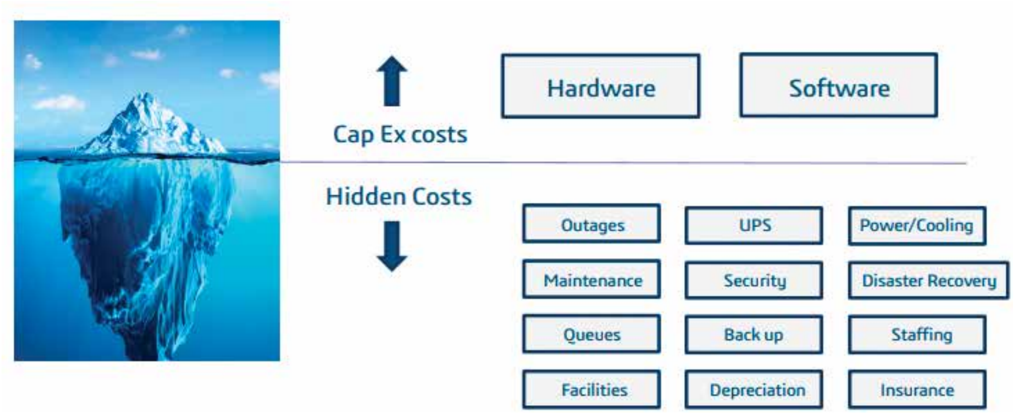

Figure 12: Hidden costs of on-premise HPC

Software as a service (SaaS) and infrastructure as a service (IaaS) on the cloud is an attractive alternative for start-ups with low barriers to entry, zero user maintenance, rapid scalability and flexible pricing. The robust portfolio of multiphysics / multiscale simulation applications discussed here are included in the comprehensive, fully collaborative, cloud native platform provided by Dassault Systèmes. The platform manages the tools, data, hardware and licensing in a cohesive modern framework, offering SaaS, IaaS and PaaS (platform as a service). All of these on-demand services work seamlessly to enable turnkey, scalable, cross department workflows.

SIMULIA simulation and analysis algorithms scale very well to accommodate HPC hardware allocated. However, considering the highly variable, burst nature of HPC simulation workloads revolving around peak production cycles, an expensive system may be under-utilized in typical daily workload scenarios. The burst cloud computing model with **3D**EXPERIENCE ensures that required resources are available for peak usage, with no cost in times of under-utilization. In many companies, data, files and results are stored and replicated multiple times, both intentionally for backup or localization purposes and unintentionally due to poor organization–all leading to excess and increasingly unmanageable disk usage. This is particularly pertinent for simulation data where very large results files can be generated. The **3D**EXPERIENCE platform eliminates unnecessary replication and improves efficiency and data backup and disaster recovery are built in.

Adding cloud-based HPC to the platform has created greater flexibility for product manufacturers. In a one-stop-shop they can access software, hardware and all the peripheral services, on-demand in a burst or sustained manner. Small companies can maintain or move to a zero IT footprint and large enterprises can leverage cloud HPC on demand during peak workloads to cost-effectively extend their simulation resources when needed,

SUMMARY

If electric vertical take-off and landing vehicles are a success, they will represent one of the most incredible leaps in the history of transportation. The biggest hurdle for industries developing eVTOL vehicles is convincing the public that the air taxi is a safe, affordable, realistic alternative to ground transportation. Digital prototyping offers a strong value in the era of urban mobility. Dassault Systèmes has a wide range of products from the **3D**EXPERIENCE platform and the SIMULIA portfolio, which offers solutions for speeding up the eVTOL development cycle. The **3D**EXPERIENCE platform offers the ability to model, analyze, simulate, visualize and experience the eVTOL vehicle in a virtual environment, with additional benefits such as enhanced collaboration and communication across all disciplines. This is even more compelling when one realizes the cloud-based **3D**EXPERIENCE platform is easily accessible to everyone, everywhere, to strengthen collaborative innovation—truly leveling the playing field for companies of all sizes.

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