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Urban Air Mobility Noise: Current Practice, Gaps, and Recommendations

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Executive Summary

Urban Air Mobility (UAM) is an opportunity for aviation to improve transportation systems across the world. While not strict definitions, representative UAM vehicle attributes include electrical vertical takeoff and landing (eVTOL) vehicles that can accommodate up to 6 passengers (or equivalent cargo), are possibly autonomous, perform missions of up to 100 nautical miles at altitudes up to 3000 ft. above ground level, have flight speeds up to 200 knots, and payloads between 800 and 8000 pounds. Along with the many anticipated benefits, there will be noise issues that need to be addressed. In 2018, NASA formed an Urban Air Mobility Noise Working Group (UNWG) to assemble noise experts from industry, universities and government agencies to identify, discuss, and address UAM noise issues.

This paper presents a set of high-level goals intended to address barriers associated with UAM noise that may hamper UAM vehicle entry into service. It summarizes the current practice, identifies gaps in the current practice, and makes recommendations to address the gaps to achieve the high-level goals in four areas of interest: Tools and Technologies, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy. The high-level goals and an abridged version of the recommendations in each area of interest are presented below.

High-Level Goals

- Document noise reduction technologies available for UAM and identify knowledge gaps for each of the four areas of interest (UNWG subgroups).
- Assess prediction capabilities for benchmark problems based on an open set of reference vehicle designs using available data.
- Assess metrics for audibility and annoyance of single-event vehicle operations using available predicted and measured data.
- Define measurement methods/procedures to support noise regulations and assessment of community noise impact, and coordinate with UAM vehicle manufacturers on development of low noise approach and takeoff procedures for piloted and automated operations.
- Examine fleet noise impacts through prediction and measurement, and characterize effectiveness of supplemental metrics for audibility and annoyance.
- Promote UAM integration into communities through mitigation of fleet noise impacts, and engagement with the public.

Tools and Technologies

Further development of validated noise prediction tools is required to support research and development of vehicles and their operations. It is recommended that:

- System noise prediction tools be further developed for application to UAM vehicles and made available to the research and industrial communities.
- Research be performed to develop conventions on how to handle control redundancies to obtain preferred low-noise trim conditions and to further develop the acoustic tools to handle aperiodic sources.
- Prediction models for the highest amplitude noise sources be validated with experimental data for isolated and installed configurations, and that flight test data be acquired to better understand variations under realistic operating conditions, particularly unsteady conditions (e.g., maneuvers and transition).
- Continued development of auralization tools be performed to allow realization of flight operations (including takeoff, forward flight, landing, and transition) for a representative range of vehicle configurations.
- A dedicated technology maturation effort be performed on the most promising noise mitigation technologies and that opportunities be sought to evaluate their efficacy in flight.

- Surrogate or other reduced order model methods be developed so that designers can quickly determine the effects of design changes on noise early in the design process, and that sensitivities be fully implemented to enable optimization of low-noise vehicle designs and operations.
- Research be conducted to more fully explore limitations in methods for assessing community noise impact of UAM vehicles in their operational environments, and to generate a software development plan that addresses the limitations of current models over time.
- Manufacturers work with appropriate organizations to develop low noise guidance for piloted operations and automated low-noise procedures for autonomous operations that are specific to their products.

Ground and Flight Testing

Several practices commonly used across the aeronautics industry should be strongly considered for near-term testing or future standardization. It is recommended that:

- Test environment constraints (e.g., ambient levels, benign meteorological conditions), similar to those in ICAO Annex 16 Vol. I and 14 CFR Part 36, be used for all tests conducted to measure UAM vehicle noise.
- Significant on-aircraft instrumentation and monitoring of the vehicle state be required due to varying levels of autonomy and potential increase in degrees-of-freedom of the flight envelope.
- The "worst" case or the noisiest mode the vehicle will fly (under automatically controlled Variable Noise Reduction System provisions) be established. Additional work is recommended to define appropriate methods to evaluate acoustic dependence and variability with respect to the vehicle state.
- A full assessment of anticipated UAM aircraft flight performance and operational environments be performed to support the development of any future certification procedures and/or standards.
- Stakeholders (including manufacturers, researchers, and certification authorities) closely collaborate in the development of new measurement approaches.
- Noise measurements above the aircraft be investigated to understand the relative importance of noise directed along the horizon and above the aircraft.
- Use of flush mounted or inverted microphones over a rigid ground plane be specified as part of any future noise certification procedures.

Human Response and Metrics

Further development of metrics and validated predictive models of human response is needed to inform decision making by UAM vehicle manufacturers and regulators. It is recommended that:

- Efforts be made to acquire/generate measured and simulated vehicle acoustic data, and to make those data available to support subjective response studies for metric and predictive model development.
- Standardized processes for measuring and cataloging ambient noise be developed, and to make those data available to support subjective response studies for metric and predictive model development.
- Until early entrants are fielded, and community noise studies can be performed, laboratory studies be performed to help inform how different the annoyance to short-term exposure of UAM vehicle noise is from that of existing aircraft noise sources. Assessments can then be made to determine the sensitivity of noise exposure estimates to changes in the metric or to its level.
- Validated models for audibility, noticeability, and annoyance to UAM aircraft noise be developed to assess their utility for assessing community noise impact.
- The transmission of UAM vehicle noise through residential and commercial structures be quantified in order to evaluate the 20 dB loss assumed by current land use compatibility guidelines.

- Measures of human response be developed and used as constraints in perception-influenced design. Ideally, such measures would be easily calculated and include sensitivities.
- Comprehensive evaluation of metrics that supplement the day-night average sound level be performed for communicating community noise impact of UAM vehicle noise.
- A laboratory test campaign be used to explore differences in perception of UAM vehicle noise between communities, so that future policy decisions are based on data representing a wide range of environments.

Regulation and Policy

It is recommended:

- That at the national level, the FAA, in collaboration with other agencies and the industry, address certification, standards, and environmental reporting for UAM noise before these vehicles enter service. This is needed so that local communities are not panicked into the establishment of ordinances that will both limit growth of the market and potentially create operationally restricted zones.
- That i) Industries be more proactive in approaching regulators to help them understand vehicle designs, noise characteristics, operating modes, etc., and to share relevant data, and ii) Regulators help the industry to understand the regulation process and policies, and identify specific data needs to bridge gaps in standards and procedures. R&D programs, technical committees, and workshops are some of the venues that such collaborations can take place, in addition to direct communications.
- To collect more data in the field through R&D programs and to leverage data from manufacturers. The data would not only help to support noise certification of UAM vehicles, but also to assist the development and validation of noise prediction capability for noise impact analyses and to identify approaches and best practices for quiet aircraft designs and for quiet flight operations.
- That regulators and policy makers work to clarify the boundaries of responsibilities in managing UAM noise, and support development of guidance for vertiport planning regarding both location identification and environmental assessment at the proposed locations.
- To develop a strategy and framework for community engagement before UAM noise concerns arise. Being prepared to address local community noise concerns early in the process will be critical to success for this market. Initial flight operations should not come as a surprise to the affected community. Modern tools such as virtual reality with auralization could provide effective ways to inform and engage the public.

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1 Introduction

1.1 Purpose

The term “Advanced Air Mobility” has been adopted by NASA to describe safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. By this definition, Advanced Air Mobility includes both “rural” and “urban” applications including cargo and passenger transport missions, and other aerial missions (e.g., infrastructure inspection). There will be a range of aircraft types performing such missions, including small and medium Unmanned Aircraft Systems (UAS), electric Conventional Takeoff and Landing (eCTOL) aircraft, and electric Vertical Takeoff and Landing (eVTOL) aircraft. Urban Air Mobility (UAM) is a challenging use case for transporting cargo and passengers in an urban environment and is a new opportunity for aviation that could revolutionize the transportation system. Emerging technologies and opportunities include electric propulsion, distributed lift (enabling lower tip speeds and increased safety through redundancy), and automated flight profile control. The integration of UAM vehicles into the transportation system is being studied by many organizations throughout the world. Conceptually, the integration will require adding vertiports within communities to serve as local transportation hubs for people and cargo. Both piloted and autonomously controlled vehicles are envisioned that will fly numerous short missions at relatively low altitudes over populated areas that have not normally been exposed to aircraft noise. The character of the noise is expected to be different from existing helicopters and general aviation aircraft. New noise exposure and annoyance from these vehicles could limit the success of integrating UAM into the transportation system [1-3].

There has been a long history of aircraft noise reduction research, and implementation of the products of that research, by industry since the early days of powered flight. The success of aircraft noise reduction comes from cooperation among government agencies, industry, and university research. Noise reduction technology development and demonstration of technical feasibility are very important, and mesh well with the development of noise regulation standards including noise limits, testing methods, and procedures. There have been many noise prediction tools and measured noise databases developed for conventional vehicles. These tools help regulators and industry assess the impact of noise. With the introduction of UAM vehicles, new tools and technologies will need to be developed to reach a similar level of confidence for predicting and reducing noise. Existing methods will still be useful; however, there is a need to identify gaps related to UAM vehicles in the current tools and in current databases so that new technology development plans can be established and prioritized. The purpose of this paper is to identify gaps/needs in UAM tools and technologies for noise prediction, validation, noise reduction, low-noise operational procedures, metrics related to human response, and in ground and flight test measurements methods.

Although noise regulation is not in its charter, NASA is at the forefront of advancing noise reduction technologies and in developing prediction methods and design tools, and has been supporting other agencies and organizations in developing robust metrics and in understanding human reception to aircraft noise. NASA already has a working relationship with organizations such as the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) in evaluating subsonic and supersonic aircraft noise. A similar relationship is envisioned wherein NASA will be providing knowledge, methods, tools, and technological evaluations about UAM and their noise to inform decision making.

1.2 Scope of Vehicles

There are many different types of vehicles being considered for UAM. NASA has developed a conceptual airspace depicting various missions that include small/medium UAS, UAM, and thin/short haul markets. Figure 1 shows the notional airspace and includes the potential UAM market in the lower right-hand side of the figure.

Figure 2 provides definitions for each of the markets shown in Figure 1, as defined by a NASA Aeronautics Emerging Aviation Markets (EAM) Tiger Team in 2017. The right-hand column describes the attributes of the vehicles; these definitions were intended by the EAM Tiger Team to be representative and not as strict definitions. UAM is recognized as a rapidly emerging market that will require quiet operations near vertiports and over noise-sensitive land uses. The vehicle attributes include: 6 or fewer passengers (or equivalent cargo), a single pilot or autonomous control, approximately 100 nautical mile missions flown under 3000 feet above ground level, flight speeds of 200 knots or less, payloads ranging from 800 to 8000 pounds, and eVTOL with either all battery power or hybrid-electric propulsion.

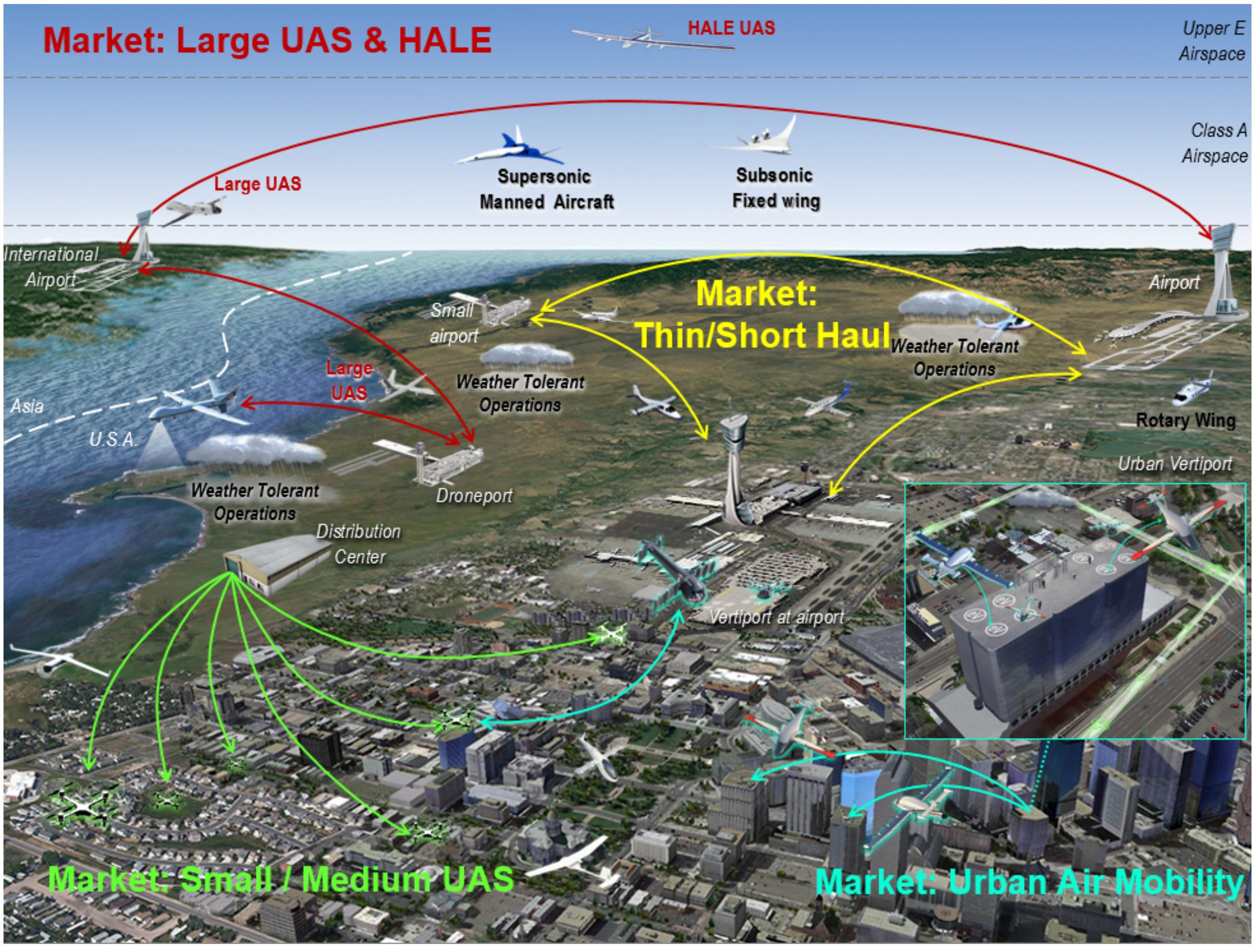
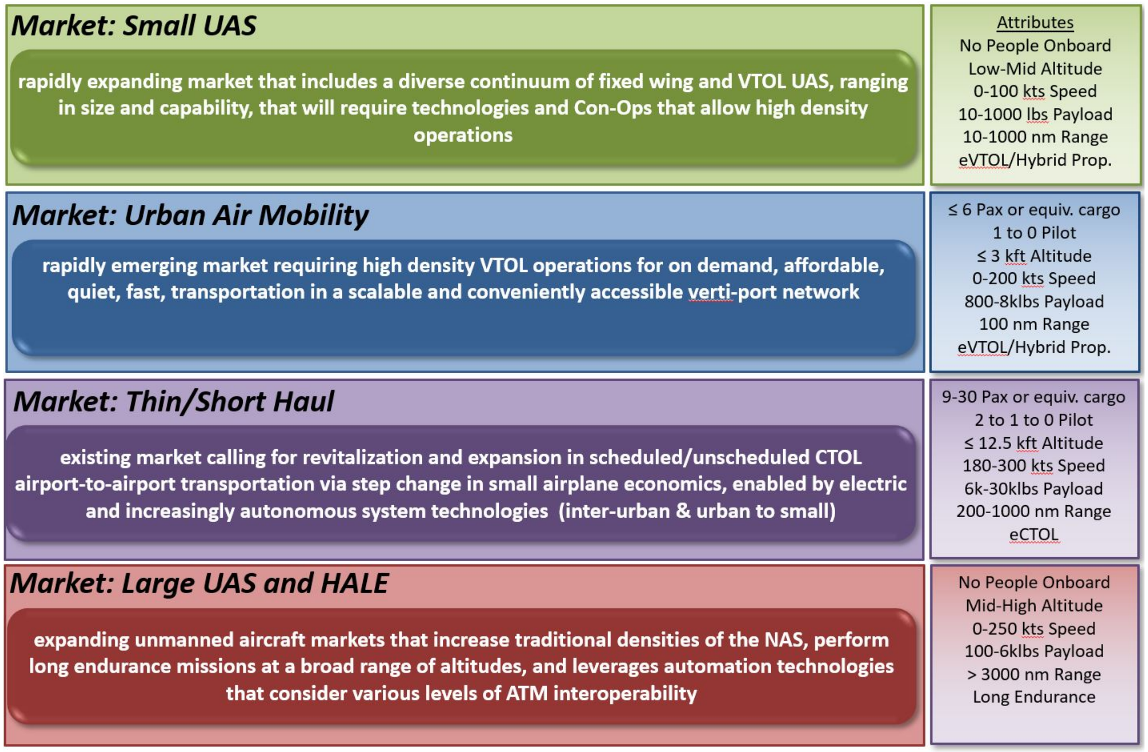


Figure 1: Integration of UAM into airspace.

Several UAM vehicle concepts include a transition of the rotor from a hovering configuration to a propeller configuration, similar to that currently used by tilting proprotor vehicles. Other concepts disengage or reduce the number of rotors used for vertical lift and rely on one or more propellers during mission cruise. A useful categorization of vehicles include “vectored thrust,” describing aircraft that use any of its thrusters for both lift and cruise, “lift+cruise,” describing an aircraft with independent thrusters for lift and cruise, that is, without thrust vectoring, and “wingless,” or multicopters, describing aircraft with thrusters for lift only. The Vertical Flight Society maintains a list of such aircraft [4]. Additionally, NASA’s Revolutionary Vertical Lift Technology (RVLT) Project has defined several reference vehicles to evaluate technologies and the technology impact on mission requirements. Details about the RVLT reference vehicles are found in Refs. [5,6], and a few are shown in Figure 3.



Market: Small UAS

rapidly expanding market that includes a diverse continuum of fixed wing and VTOL UAS, ranging in size and capability, that will require technologies and Con-Ops that allow high density operations

Attributes
No People Onboard
Low-Mid Altitude
0-100 kts Speed
10-1000 lbs Payload
10-1000 nm Range
eVTOL/Hybrid Prop.

Market: Urban Air Mobility

rapidly emerging market requiring high density VTOL operations for on demand, affordable, quiet, fast, transportation in a scalable and conveniently accessible verti-port network

≤ 6 Pax or equiv. cargo
1 to 0 Pilot
≤ 3 kft Altitude
0-200 kts Speed
800-8klbs Payload
100 nm Range
eVTOL/Hybrid Prop.

Market: Thin/Short Haul

existing market calling for revitalization and expansion in scheduled/unscheduled CTOL airport-to-airport transportation via step change in small airplane economics, enabled by electric and increasingly autonomous system technologies (inter-urban & urban to small)

9-30 Pax or equiv. cargo
2 to 1 to 0 Pilot
≤ 12.5 kft Altitude
180-300 kts Speed
6k-30klbs Payload
200-1000 nm Range
eCTOL

Market: Large UAS and HALE

expanding unmanned aircraft markets that increase traditional densities of the NAS, perform long endurance missions at a broad range of altitudes, and leverages automation technologies that consider various levels of ATM interoperability

No People Onboard
Mid-High Altitude
0-250 kts Speed
100-6klbs Payload
> 3000 nm Range
Long Endurance

Figure 2: Markets and vehicle attributes identified by the NASA Emerging Aviation Markets Tiger Team.

Figure 3: Several NASA RVLT reference vehicle configurations.

1.3 Managing Aviation Noise

A balanced approach is typically used to manage aviation noise that includes reduction of noise at the source, land use planning and management, noise abatement operational procedures, and operational restrictions on aircraft [7]. At the aircraft noise source level, noise reduction technologies have been integrated into aircraft design to reduce aircraft noise levels continuously over the years (Figure 4). By integration of effective noise reduction technologies and the associated noise certification stringency imposed by regulation, communities near airports are exposed to significantly less noise from an individual airplane flight as compared to the same communities 60 years ago. This successful technology integration and stringency has contributed to a thriving aviation market that would be more limited had noise issues remained unmitigated. Even with this progress, there is opposition today that prevents aircraft operation expansion at some airports. At the operational level, the aircraft flight profiles, flight tracks, and even flight schedules (e.g., curfews) are managed to reduce noise exposure of sensitive areas around airports. Land use planning guidelines are structured to maintain geographic separation of the effects of airport operations from the encroachment of neighboring community development. However, these guidelines are not always effective as development does sometimes encroach on airports. Further, community outreach is considered important and effective especially when a change in noise is introduced in the system.

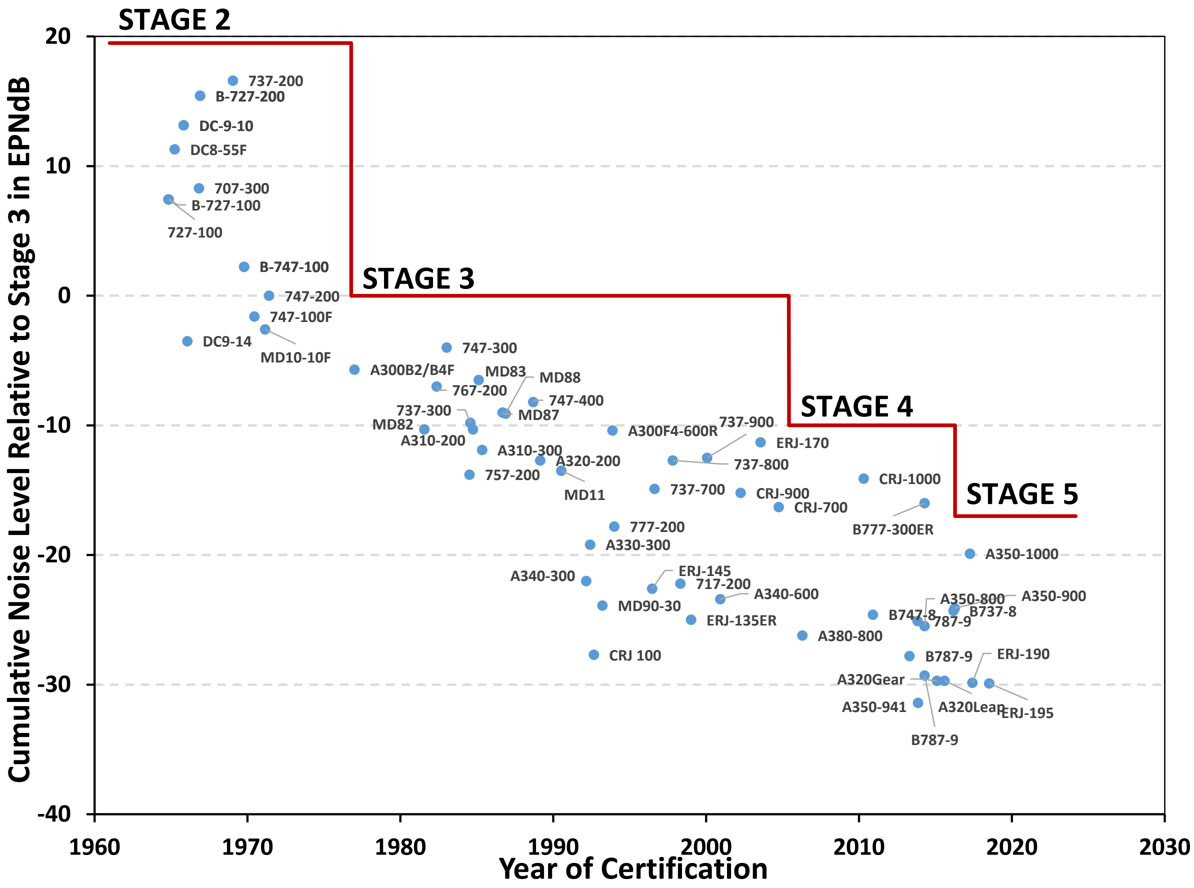


Figure 4: Commercial transport noise cumulative noise level reduction relative to stage 3.

1.3.1 Helicopter Noise

Of the aircraft in service today, conventional helicopters (inclusive of tiltrotors) are the most similar to UAM vehicles in terms of their operations. Helicopters operate from heliports that can be close to residential communities. Overflights take place at lower altitudes compared to fixed-wing aircraft unless the vehicles are operating near an airport. A study published by the National Academy of Sciences addressed what is currently known about community annoyance of helicopter noise [8]. The study included acoustic and non-acoustic factors, and differences with fixed-wing aircraft annoyance. A primary objective was to explore if helicopter noise is more annoying than fixed-wing aircraft noise. Surveys were conducted for residents in three urban areas near airports with exposure to commercial helicopters and fixed-wing aircraft. The results did not conclusively find differences in annoyance between light civil helicopter noise and fixed-wing aircraft noise for comparable sound exposure levels.

Nevertheless, noise complaints regarding helicopters continue to be a problem. Complaints have been registered with the FAA in areas such as New York City [9], Los Angeles [10], and Hawaii [11]. Overflights by the air tour industry in national parks such as the Grand Canyon have also been an issue for many years. Consequently, some operations have been restricted. There are lessons and good practices that can be learned from helicopter noise that will benefit UAM, e.g., the Fly Neighborly / Environmental Working Group [12].

1.3.2 UAM Noise

For UAM, there is the potential that new populations will routinely be exposed to aircraft noise because UAM vehicles are anticipated to be flying in much greater numbers than helicopters. Historically, changes in noise over a populated area have been met with resistance. This resistance can be in the form of noise complaints, which can potentially call for more strict local noise ordinances that can restrict vertiport siting. Vertiports will likely be located in populated areas where the UAM noise will be the highest due to low altitude flight and landing/takeoff operations. All of these considerations are similar to issues involving helicopter noise today. Community outreach will be important to keep the public informed and help mitigate noise complaints.

A challenge unique to UAM noise assessment is that one aircraft design may have an entirely different acoustic signature from another design in terms of its spectral and temporal characteristics. This is less the case for jets and for helicopters. This variability may limit the utility of simple sound level metrics such as A-weighted sound pressure level, which correlate well when comparing changes, e.g., in the number or magnitude of otherwise similar operational sound events. Different metrics may be needed to compare the acoustic impact of these new vehicles because their sound differs in more ways than just amplitude.

1.4 UAM Noise Working Group

In response to the need for quiet design and operation of UAM vehicles, NASA extended their Acoustics Technical Working Group (TWG) to include UAM and formed the “UAM Noise Working Group (UNWG).” The first exploratory meeting was held at the NASA Langley Research Center in April 2018, and the group meets semiannually, alternating between the NASA Langley and NASA Glenn Research Centers. The UNWG has attracted subject matter experts from industry, government agencies, and academia, for coordinating acoustic work for UAM. (More information about the organization of the UNWG is provided in Appendix C). This paper is one of the first products from the UNWG, and serves to address the first high-level goal listed in Section 1.4.1. The scope of vehicles was also discussed within the UNWG, and there was general agreement that the UAM vehicle attributes shown in Figure 2 represent a good starting point for evaluating noise.

1.4.1 High-Level Goals

The UNWG has developed goals aimed at addressing key issues associated with UAM noise. There are four subgroups in the UNWG: Tools and Technologies, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy. Each subgroup developed their own set of goals. These were rolled up into the following set of overarching, high-level, goals of the UNWG:

- Document noise reduction technologies available for UAM and identify knowledge gaps for each of the four areas of interest (UNWG subgroups).
- Assess prediction capabilities for benchmark problems based on an open set of reference vehicle designs using available data.
- Assess metrics for audibility and annoyance of single-event vehicle operations using available predicted and measured data.

- Define measurement methods/procedures to support noise regulations and assessment of community noise impact, and coordinate with UAM vehicle manufacturers on development of low noise approach and takeoff procedures for piloted and automated operations.
- Examine fleet noise impacts through prediction and measurement, and characterize effectiveness of supplemental metrics* for audibility and annoyance.
- Promote UAM integration into communities though mitigation of fleet noise impacts, and engagement with the public.

1.5 Description of Sections

The remainder of this paper is organized along the lines of each of the four UNWG subgroups. Following a brief introduction, each section discusses the current practice, gaps in the current practice when applied to UAM noise, and recommendations to address the gaps to achieve the high-level goals. This paper is not meant to be a complete literature review, but does offer a sufficient number of references to support its assertions.

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* The term "supplemental metrics" in this paper refers not only to those metrics "that supplement the impact information disclosed by the DNL metric," per the FICON [13] definition, but more generally to those applicable to audibility and annoyance.

2 Tools and Technologies

2.1 Introduction

This subsection is primarily concerned with noise prediction tools supporting research and development of noise reduction technologies, design of UAM vehicles for compliance with noise certification requirements, and assessment of community noise impacts from UAM operations. The analyses typically follow (all or part of) a source-path-receiver paradigm, in which source noise emissions are propagated through the atmosphere along a path(s), for immission by the receiver(s). Each element is discussed below, with some emphasis on UAM vehicle source noise due to its unique nature.

2.1.1 Source Noise

UAM vehicle source noise differs from that of existing rotorcraft. For vertical lift, it is anticipated that a larger number of rotors will be used to lift UAM vehicles rather than the one or two rotors used on conventional helicopters and tiltrotors. Unlike conventional rotorcraft, the rotors on some UAM vehicles may operate with variable rotational speed, have lower tip Mach numbers, and have different propulsors for different functions (e.g., a pusher propeller for forward flight in combination with rotors for vertical lift). These features of UAM vehicle rotors will change the frequency content and temporal character of the rotor noise relative to conventional rotorcraft.

Interactions between the rotors and with the airframe components are also expected to change the character of the noise relative to conventional rotorcraft. Some interactions are depicted in Figure 5 and include Blade-Vortex Interaction (BVI), Blade-Airframe Interaction (BAI), Fuselage-Wake Interaction (FWI), and steady rotor loading. Many other noise sources not depicted below are possible. For example, rotor pairs in a coaxial configuration can have interrotor interference, and rotors imbedded in ducts will interfere with the support structures (stators, vanes, etc.).

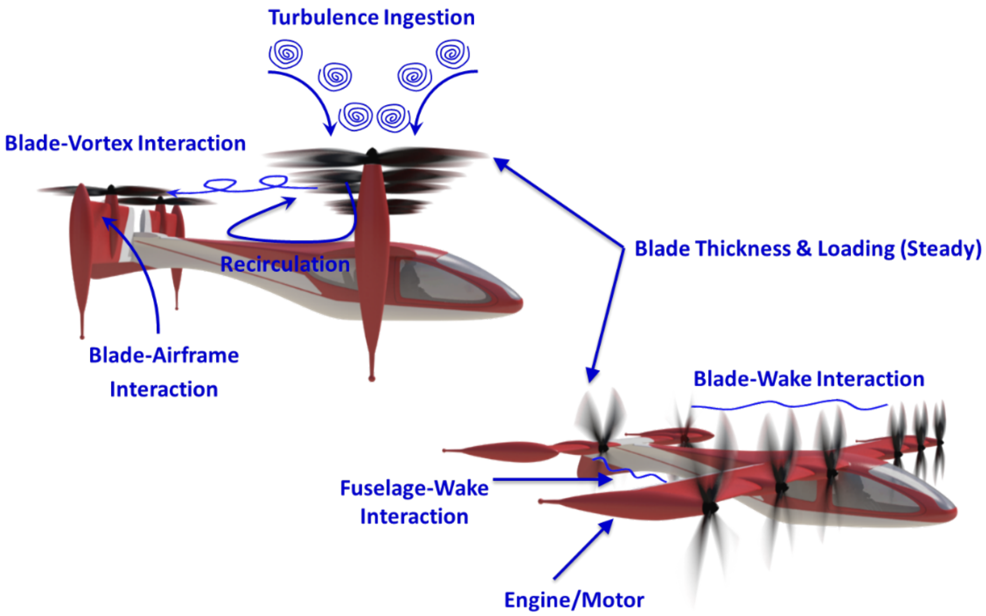

Figure 5: Some potential noise sources on a UAM vehicle.

In conventional rotorcraft, BVI noise (due to a parallel blade/vortex encounter) can be a dominant source in level flight and is typically a dominant source in descent. For UAM vehicles, BVI noise is possible for the vertical lift or transition segments, but should be less dominant than conventional rotorcraft if the rotor tip speeds are lower. This interaction could be an intrarotor or an interrotor effect (similar to a conventional tandem rotorcraft) due to expected relative rotor placement. In cruise flight, BVI could be present, but less dominant, if the rotors become propellers. However, some configurations can have aft propellers that are affected by the wakes of propellers which are forward of them.

In conventional rotorcraft, BAI is usually less of a noise source and more of an influence on the trim state of the vehicle because the rotors are generally not close to airframe. In many UAM vehicles, rotors and propellers may be close to wings – whether at the leading or trailing edge. This proximity affects the flowfield on the wing, causing unsteady loading at the blade passage frequency (BPF), making the wing itself an additional noise source. The potential flowfield that the wing imposes consists of periodic impulses on the rotor that increase the unsteady loading components on the rotor (also a noise source). The same BAI-like effects can occur if the rotor passes near the fuselage, e.g., vehicles that resemble a tiltrotor in cruise. If the rotors are behind the wing or fuselage, then the rotor ingests the wake from the wing or fuselage, increasing the unsteady loading noise from the rotor, resulting in FWI noise. Due to the number of rotors and their placement on many proposed UAM vehicles, BAI and FWI are anticipated to be more important sources than in conventional rotorcraft.

Due to the anticipated lower rotor tip speeds and the probable Blade-Wake Interaction (BWI) from multiple rotors in proximity to one another, the expectation is that broadband noise will be much more important for UAM vehicles than for conventional rotorcraft. Expected broadband noise sources include those from rotor "self noise" (from each rotor separately), BWI noise (from both interrotor and intrarotor interactions), and atmospheric Turbulence Ingestion Noise (TIN).

The rotors will likely be driven by electric motors and powered by either batteries or hybrid-electric systems. Electric motors that drive the rotors may be an additional noise source for UAM that are not typically present in conventional rotorcraft. Hybrid-electric systems could include auxiliary power units or turbine power generators. These devices, too, will have unique noise characteristics.

2.1.2 Sound Propagation

The physics of sound propagation of UAM vehicle noise is no different than that of other noise. However, because the operating environments of UAM aircraft, though currently not well-defined, will likely include vertiports, urban canyons, and densely populated areas, there is more in common with rotorcraft operations than with aircraft operations in the vicinity of airports. Local wind and atmospheric conditions in an urban setting affect not only UAM flight performance, but also sound propagation. It has been proposed that near-term entry-into-service aircraft may takeoff and land in repurposed environments, such as parking lots or roof tops. Future vertiports may be very different from the environments used by near-term entry-into-service aircraft and from current heliports. These vertiports will likely have a wide range of configurations and will include reflective structures (e.g., buildings) close to aircraft.

2.1.3 Noise at the Receiver

Other than those metrics commonly used for noise certification and community noise assessment, calculation of alternative metrics, e.g., time-varying loudness used in the prediction of audibility, will likely require an alternative or augmented set of analysis tools. Such measures are the subject of Section 4. Noise at both outdoor and indoor receivers is of interest because people react to noise differently in different settings.

Although not the focus of this paper, interior noise for UAM cabins could become an issue for passenger comfort. Noise levels will depend on the specific vehicle and on what treatments can be used to reduce the sound. The expectation is that the dominant noise sources contributing to UAM cabin noise will differ from that of conventional rotorcraft. These sources include those associated with exterior sound radiation but will also include structure-borne sources such as electric motors and hybrid generators that may be dominant contributors to interior noise due to their proximity to passengers. Some UAM aircraft may employ a gear box, a dominant source of cabin noise on conventional rotorcraft.

2.2 Current Practice

The set of noise prediction tools supporting research and development of noise reduction technologies, and design of UAM vehicles for compliance with noise certification requirements, have much in common. Those supporting assessment of community noise impact significantly differ. This subsection is organized along those two lines.

2.2.1 Research and Design Tools

2.2.1.1 System Noise Prediction

System noise prediction tools, such as NASA's second generation Aircraft Noise Prediction Program (ANOPP2) [14], are often used to support research and design. They typically integrate all elements of the source-path-observer paradigm, including source noise definition (inclusive of installation effects), propagation, and noise certification metrics calculations at the set of prescribed observer points and operating conditions, see Figure 6. Most are in the form of an observer dominant time-marching simulation of an aircraft flight operation, in which the propagation of sound to the far field (ground) observer is calculated based on the source noise definition at the retarded time and position. Noise certification regulations prescribe noise levels in specific metrics (effective perceived noise level (EPNL), sound exposure level (SEL), etc.) which require the design of vehicles to meet noise limits during flyover, takeoff, and landing operations. They may also be used to generate metrics for use in community noise assessments, see Sections 2.2.2 and 3.2, when empirically derived data are unavailable.

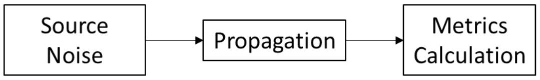

Figure 6: Elements of system noise prediction.

Trim

For a given vehicle configuration, flight profile, and flight condition, the trimmed state of the vehicle is first determined. Achieving a prescribed steady state flight condition requires that the mean forces and moments acting on the vehicle sum to zero. When this state is achieved, the vehicle is said to be "trimmed." In the trimmed condition, the control surface configuration of the vehicle corresponds to the desired flight condition. For conventional rotorcraft, typically some combination of blade pitch control and vehicle orientation is used to trim the vehicle to a given flight condition or to perform a maneuver. There are a few possible redundant controls (such as elevator controls, rudder controls, tilting of rotors, etc.); however, over many years of rotorcraft operations, there are conventions to handle the redundancies.

Source Noise

Isolated Sources

A hybrid approach is typically used for prediction of deterministic (tonal) rotational noise, as depicted in Figure 7. The hybrid approach determines blade loadings using one method, i.e., a flow solver, blade motions with another method, i.e., a computational structural dynamics (CSD) solver, and the resulting acoustics from yet another method, i.e., an acoustics solver. Blade loadings may be determined from a computational fluid dynamics (CFD) analysis, inclusive of lattice Boltzmann methods (LBM), or from comprehensive analysis (CA) methods. In either case, accurate blade geometry definition is required. The blade motion is determined by applying the aerodynamic loadings to a CSD method, most often from a comprehensive analysis. There is an iteration between the blade loading and blade motion solvers until blade loadings, blade motions, and the trim state converge. The acoustic prediction is subsequently performed with an acoustics solver that may be part of a system noise prediction tool. The acoustics solver typically is one with a solution to a subset of the Ffowcs Williams-Hawkings (FWH) equation [15]. This subset normally contains just the deterministic noise sources, valid in both the near and far field. The far-field solution then may subsequently be propagated to an observer on the ground, often with the assumption of a compact source.

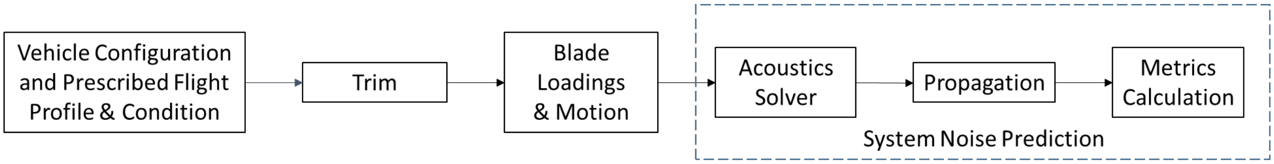

Figure 7: Hybrid approach for prediction of tonal rotational noise.

Semiempirical models are often used for some nondeterministic (broadband) noise sources, e.g., blade self noise. Other models that employ the lattice Boltzmann method can also compute some components of broadband noise.

A more detailed discussion of prediction methods for tonal and broadband rotational noise, applicable to UAM vehicles, is provided in Appendix D. Some familiarity with that material will aid the reader in understanding subsequent topics in this section.

Several prediction methods exist for turbomachinery noise, e.g., see Ref. [16], that are applicable to hybrid-electric UAM vehicle configurations.

Installed Sources

Propulsion airframe aeroacoustic (PAA) effects, resulting from installation of propulsion system components on the airframe, include both aerodynamic and acoustic effects. Aerodynamic effects modify the source noise generation, e.g., rotor-rotor interactions in a multirotor configuration. Acoustic effects modify the noise propagation, e.g., reflection of noise off the fuselage. While many installations have the detrimental effect of increasing the noise of the installed source relative to the isolated source, some installation effects can be beneficial when incorporated in the development of noise reduction technologies, see Sections 2.2.1.2 and 2.3.1.2. PAA effects are highly configuration dependent.

A more detailed discussion of installation effects, applicable to UAM vehicles, is provided in Appendix D.

Validation Data

Noise prediction methods need data to ensure that existing codes capture the important effects to evaluate and design UAM vehicles. In recent years, there have been experimental measurements made with the goal of outlining issues associated with the design of this new class of vehicles. These experiments include both simple and complex configurations. While these experiments explore certain aspects of these issues, typically these experiments are on smaller scale vehicle components. It is not clear if the results of the small-scale experiments (e.g., Refs. [17,18]), having scale and blade aspect ratio differences far outside the knowledge base, represent that of full-scale UAM vehicles.

Propagation

Sound propagation tools are used to propagate the airborne source noise to a set of observers on or near the ground. A compact source is often assumed, and the set of ground observers is typically stationary. Two approaches for sound propagation are commonly adopted; a time domain approach within a source dominant simulation, and a frequency domain approach within an observer dominant simulation. The two approaches result in comparable noise metrics at the observer(s).

Propagation tools need to account for at least three effects: spreading loss, time delay, and atmospheric absorption. Additionally, ground plane reflections need to be taken into account for observers above the ground plane. For very low flying vehicles, more sophisticated ground plane reflection models accounting for spherical waves (versus plane waves) are required. Some researchers have begun to integrate UAM vehicle noise prediction with urban sound propagation [19].

Auralization

Auralization is a technique for creating audible sound files from numerical data, typically data describing the noise at the source. Within that context, auralization includes operations for sound synthesis and propagation. Auralization tools complement system noise prediction tools and can serve several purposes: they provide a means of communicating noise exposure to stakeholders in a natural, experiential form; they provide feedback to the noise analyst regarding the system under design; and they serve as an integral element of perception-influenced design of new air vehicles, see Section 4.3.1.1. The state-of-the-art is detailed in Ref. [20].

2.2.1.2 Source Noise Reduction Technologies

Source noise mitigation strategies are highly configuration dependent. Generally, in the acoustic far field, several key relations are present for subsonic rotational (thickness and loading) noise sources.

Items that strongly affect thickness noise include blade geometry (thickness noise increases by 6 dB for every doubling of thickness) and quantities such as surface acceleration and surface Mach number (due to motion). Exacerbation of these effects occurs when the direction of these components is oriented toward the observer.

Items that strongly affect loading noise (tonal and broadband) are quantities such as surface pressure (loading) and how fast this surface pressure (loading) changes, and surface Mach number (due to motion). The largest effect comes when the directions of the surface components (due to motion) are oriented toward the observer. Faster changes in surface pressure (loading) tend to increase loading noise, as does higher mean surface pressure (loading).

Additional relations exist in the near field (applicable to cabin noise), but are not discussed here.

Development of practical and effective noise reduction technologies often requires a mixed fidelity analysis, i.e., high fidelity analysis of the component under development, within the context of a lower fidelity system noise prediction. Clearly, examination and mitigation of the adverse effects of those technologies on the performance of the vehicle are required. Some current noise reduction strategies for rotorcraft that are applicable to UAM include:

- For isolated rotors and propellers, increasing the number of blades, optimizing the blade airfoil shapes, optimizing the blade planform shape, reducing the rotational rate, avoiding blunt trailing edges, avoiding gaps if there are flaps, etc.
- For rotor-airframe interactional noise effects, increasing the rotor/airframe separation distances, placing rotors above the airframe supports rather than below them, and avoiding pusher propeller configurations that are in proximity to a fuselage, rotor wake, or wing wake.
- For rotor-rotor interactional noise effects, adjusting the rotor blade rotational speed or phase relative to other rotors, adjusting the relative rotation direction between rotors, and placing the rotors at appropriate distances from one another.
- Configurations that utilize sound absorptive surfaces (e.g., ducted props with liners), and that exploit beneficial PAA effects including diffraction and reflection of acoustic waves around vehicle surfaces, and refraction of acoustic waves (e.g., by flow velocity gradients).

A status of helicopter noise reduction technology, as of 2015, can be found in Ref. [21].

2.2.1.3 Vehicle Design

System noise prediction tools are often integrated within multidisciplinary design, analysis, and optimization of vehicles. Such analyses require “fast” methods that can provide the correct trends due to configuration changes. Use of these relative trends inform design decisions and provide the ability to assess trade-offs between those design decisions. Designers’ interests typically emphasize the importance of knowing relative value changes over knowing absolute values. They also emphasize knowing the influence of important sources rather than the influence of all sources.

One of the most efficient design methods available is gradient-based optimization. This implies that the methods used must supply sensitivities of the objective function(s) to design variables. The most efficient methods provide analytical gradients directly from the method. Development of these analytical gradients remains a very large challenge, though some progress has recently been made. Some acoustic codes, some CFD codes, and some CA codes now provide analytical derivatives directly. However, these methods coupled in an adjoint formulation are currently far too expensive for a designer to use.

For some methods, analytical derivatives may not be directly available. However, finite difference methods can be used to compute approximations to the derivatives. These methods need to be made more routinely available. Like analytical derivatives, they are also far too expensive for routine use by designers.

Current fast design methods revolve around surrogate models that provide changes of parameters in relation to other known parameters, and are searched or used in computations to include the effect of changes. However, these surrogate models need measured data or other computational models to create them. The surrogate models used in design, however, rarely include acoustics.

2.2.2 Community Noise

2.2.2.1 Assessment Tools

The ability to assess community noise impacts from UAM operations is needed to determine land use compatibility, and for National Environmental Policy Act (NEPA) studies if federal actions are involved. The ability is also needed for state and local environmental assessment protocols, such as the California Environmental Policy Act (CEQA), for research and operational purposes, and for communication with the public. These activities require different levels of modeling fidelity and potentially different modeling approaches than those used for design. Aggregated noise impacts (historically assessed by considering annual average daily noise exposure) do not require the precision needed for single event analyses, e.g., to gauge acceptability of a vehicle operation in the presence of background noise or to optimize a flight trajectory to reduce noise at critical receptors. It is likely that multiple UAM noise assessment tools will be needed to meet regulatory and policy needs as well as research, design, and operational needs.

In the U.S., the FAA Aviation Environmental Design Tool (AEDT) is the required tool to assess aircraft noise and other environmental impacts due to federal actions at a civilian airport or vertiport, or in U.S. airspace for commercial flight operations. AEDT and prediction tools with the same or similar modeling technologies are used in other countries as well [22]. For fixed-wing aircraft, AEDT calculates noise contours using Noise-Power-Distance (NPD) data specific to each aircraft. For a fixed-wing aircraft, a performance model determines the power required to execute the specified flight operation. For helicopters, AEDT calculates noise contours using measured Noise-Operating Condition-Distance (still termed NPD) data specific to each vehicle, with the operating condition, e.g., hover, directly specified through the flight operation. For UAM vehicles, there exists neither a measured NPD database, nor a generic performance model. Furthermore, given the wide variety of UAM vehicle concepts, performance models will likely be vehicle specific. Therefore, current assessments are limited to either i) utilizing the fixed-wing or helicopter modes in a compromised fashion, or ii) utilizing the ‘fixed-point flight profile’ in which the noise is specified as a function of distance for each constant flight condition (segment) along the flight track. The latter puts the onus on the user to trim the vehicle for each segment, removing the need for a built-in performance model.

For computing aircraft noise from U.S. Department of Defense operations at military or joint-use civilian installations, the NoiseMap suite of tools is used. This tool set includes an integrated model NMAP [23] (similar formulation as AEDT) for legacy aircraft in conjunction with the simulation tool Advanced Acoustic Model (AAM) [24] for helicopter, tiltrotor, and high-thrust and thrust-vectoring aircraft. At the core of NMAP is the NOISEFILE database with NPD data and reference spectra, while AAM relies on 3D spectral noise data (spheres) representing source noise emission characteristics. These tools output a variety of metrics and levels at receptor points. Both NMAP and AAM require the user to prescribe the flight trajectory and do not include vehicle performance modeling capability. AAM has the ability to generate receptor time history data in 1/3 or 1/12 octave band format and has been interfaced with partial time varying loudness capability for assessment of UAM sounds against background noise [25,26].

2.2.2.2 Low Noise Operations Design

While acoustics-based design and introduction of noise reduction technologies on the vehicle have been successful in reducing aircraft noise emissions at the source, another way to reduce ground noise is through operational planning or trajectory optimization. For example, the general suggestion for helicopters during takeoff is to depart at a high rate of climb and maintain a high altitude during cruise to maximize propagation distances. Approach can be a bit more complicated, as the encountered aerodynamic states are prone to BVI and can severely increase both ground noise levels and impulsiveness, the latter being a sound quality attribute known to be problematic. Several efforts have shown significant noise reductions can be achieved during approach, in excess of 6 dB, by tailoring deceleration and flight path angles [27]. Preferably, operational planning should be vehicle specific (at a minimum, to each vehicle class), but can require a great deal of flight testing or simulation time to determine appropriate procedures. To study this, several recent flight tests [27] have been executed involving many helicopter types to understand noise abatement techniques during approach and maneuvers, and to determine generalities in procedures amongst the vehicles tested [28,29]. To simplify guidance for pilots, the Fly Neighborly / Environmental Working Group [12] has published generalized guidelines and noise abatement procedural information to aid in minimizing acoustic impacts, and has gained widespread support amongst operators and communities throughout the U.S.

2.3 Gaps

2.3.1 Research and Design Tools

2.3.1.1 System Noise Prediction

Several gaps in system noise prediction are present and hamper the ability to perform comprehensive UAM vehicle noise assessments. These include:

- Lack of an integrated method within the tool chain depicted in Figure 7 for prediction of broadband self noise [30] in a rotating frame. A more generalized broadband self noise method, accounting for effects such as cambered airfoils, etc., has not been developed.
- Lack of integrated acoustic scattering prediction codes. The scattering methods themselves often assume a relatively simple scattering body shape. A method to incorporate/evaluate these tools and generalize them to more complex geometries in a robust manner is needed.

Trim

Because the trim of the vehicle is configuration dependent, two vehicles with completely different configurations (e.g., a conventional main rotor/tail rotor helicopter versus a quadrotor UAM vehicle) can fly the same flight condition, but will do so in a completely different manner. With the expected introduction of multiple rotors (specifically, more than two rotors) and the ability to change parameters such as the rotor rotational speed (measured in revolutions per minute, RPM), UAM vehicles introduce multiple redundancies that enable different methods to fly the same flight condition for the same vehicle. The choice of how to control the vehicle to achieve trim can have a major influence on the noise generated. Current trim methods are well equipped to handle multiple rotors with a specified control strategy. These methods often impose, or strive for, a periodic solution on each rotor while including some rudimentary potential aerodynamic interactions.

For UAM applications, gaps in trimming methods include:

- A determination of which trim methods used in CA codes are best suited for vehicles with variable RPM rotors and vehicles that use RPM for control.
- A determination of how to apply computationally more practical loose coupling methods to cases with variable RPM. In the past, CFD/CSD tight coupling methods have been applied on a limited basis to very high rate maneuvers, and CFD/CSD loose coupling methods have been applied to periodic cases.
- Development of fast methods to include installation effects in the vehicle trim. Computationally intense CFD/CSD loose coupling methods and/or LBM can currently include these effects.
- Development of conventions on how to handle redundancies to obtain preferred low-noise trim conditions.

Source Noise

Isolated and Installed Sources

Several gaps exist in source noise modeling including:

- Knowledge of when aperiodic versus quasiperiodic methods are required. For helicopters, that point is when the time scale of the maneuver is close to the time scale of the rotor revolution.
- Robust aperiodic time domain methods. Most time domain acoustic solvers have the ability to perform aperiodic predictions; however, these have not been routinely used because the assumption of periodicity has been of value.
- Electric motor noise model(s) for this class of vehicle that are suitable for integration into existing system noise prediction frameworks. For hybrid-electric configurations, the existing prediction methods for turbomachinery noise are applicable.
- Assessment of the importance of BWI and TIN noise for UAM vehicles, and development of general prediction methods if found to be needed.
- Lack of computationally efficient tools for design. Some methods, such as LBM, can perform trade studies using a very coarse mesh as part of a design process, but remain computationally intensive. Empirical and semiempirical models, e.g., FRAME [31], offer the potential to provide computationally efficient solutions; however, additional development is needed for application to UAM vehicles.
- The effect of wakes on the rotor aerodynamics and acoustics needs to be examined in detail because many UAM vehicle concepts include pusher propellers for forward flight. Noise induced by unsteady loading on a propeller/rotor in a wake deficit region, e.g., behind a wing or pylon, can be broadband or periodic in nature depending on the position of the propeller/rotor relative to the wake. If the rotor is sufficiently far from the structure (such that the wake is diffuse), the noise will be more broadband in nature. However, if the rotor is in proximity to the structure, then the wake can appear as a periodic unsteady loading and generate impulsive noise.

Validation Data

There is a need for full-scale isolated propeller/rotor noise data across the anticipated flight regime. For source noise reduction technology development, there is a need to understand interactions between propellers/rotors based on spacing, rotational speed differences, rotor phasing, etc., across the anticipated flight regime. For all configurations, examinations with and without a fuselage present are needed. The controlled environment of an acoustically treated wind tunnel for these measurements is ideal. If only subscale models are possible in a wind tunnel, then scaling laws need development to assess the effects at full vehicle scale.

Flight test data will aid in understanding the variations in noise due to external factors (e.g., winds) and operational aspects that cannot easily be quantified in the wind tunnel (e.g., maneuvers, transition between flight conditions). Maneuvers, specifically the transition between vertical and forward flight, need to be quantified so that prediction methods can be used with confidence.

In order to calibrate system noise prediction codes, there is a need to establish, through measurements, the relative importance (source noise breakdown) of dominant noise sources of archetypal vehicle configurations and their variation with parameters such as velocity, weight (or rotor thrust), etc.

There is a need to measure and assess the importance of unsteadiness of broadband noise to support human response testing and metrics assessments.

Propagation

There is a need to better integrate advanced propagation tools capable of handling wind and temperature effects (refraction) and urban environments (reflection and diffraction) in system noise prediction and auralization tools.

Auralization

The perception of sounds differs between those with and without temporal variations. Temporal variations can occur on short (fractions of a second) and long (many seconds) time scales. Auralization tools are currently not available for short time scale modulated broadband noise. Improvements to auralization of vehicle maneuvers (long time scale) and source noise unsteadiness (short and long time scales) are also needed.

2.3.1.2 Source Noise Reduction Technologies

There are a number of possible noise mitigation technologies available in the design space, and many possible unconventional concepts to explore. There is a knowledge gap in how these technologies can be effectively applied to UAM vehicles. Some examples include:

- Rotor spacing: Interrotor spacing (horizontally, vertically, and axially) for multirotor UAM vehicles can have an impact on noise. Placement of these rotors should minimize interactional aerodynamic effects between rotors and between rotors and airframe components. Most conceptual vehicles with multiple rotors show the rotors in a very regular pattern. Irregular rotor or blade spacing could be used to modify the interactional aerodynamics. For example, an irregularity could be rotor “stacking” one above another – this is an example of “axial” spacing. Irregular interrotor spacing appears largely unexplored.
- Blade spacing: Regular (even) interblade spacing on UAM vehicle rotors is typical, as it is for conventional vehicles. The exception is the “fan-in-fin” concept, which often uses many irregularly spaced blades (and irregularly spaced and oriented stator vanes). Irregular rotor blade spacing appears unexplored, except for a few studies many years ago.
- Blade length: In addition to blade spacing on rotors, blades on each rotor are typically all the same length. Rotors having different blade lengths are unexplored for UAM vehicles. For example, with a 4-bladed rotor, each opposing blade could be the same length, but each opposing blade set could be a different length. Use of CA codes for rotors with blades of different lengths is possible, but is challenging.
- Rotor phasing: Another concept for interrotor control is rotor phasing. This concept involves manipulating the relative azimuthal position of each rotor to reduce noise at a far field observer. Depending on the strategy employed, noise reduction can come about through a reduction in radiation efficiency (a global effect), or through superposition (a directional effect). Both strategies require maintenance of precise rotor azimuthal positions relative to other rotors, and are likely applicable only to vehicles with rotors having the same rotational speed.
- Active control: Active control of blades has been a research topic for conventional rotorcraft for a long time. Application of active control to UAM vehicles presents an additional challenge due to the higher operational frequencies. On very small vehicles, RPM control is used because the

combination of motor torque, response, etc., and rotor inertia allow for such control. On larger vehicles, it is likely that this will not be possible due to the higher rotor rotational inertias, etc. Active control on larger vehicles could require either a swashplate to control all blades or individual blade devices for control. Current on-blade controls (e.g., flaps, piezoelectric patches) do not have enough control authority for UAM rotor control.

- Exterior liners: For the case where rotor-fuselage interaction is present, external liners or porous media on the fuselage could be used to mitigate noise radiated from the fuselage due to unsteady loading.
- For electric motor noise, vibration isolation and reduction of acoustic radiation efficiency needs to be explored.

2.3.1.3 Vehicle Design

There is a need to further develop and implement sensitivities throughout the design chain. Deficiencies include the lack of sensitivities in broadband noise predictions, scattering, and propagation for other than a straight ray.

As previously indicated, surrogate models used in design rarely include acoustics. Filling of this large gap in capability is necessary if acoustics is to be directly included in current design methods.

2.3.2 Community Noise Prediction Tools

2.3.2.1 Assessment Tools

There are currently no UAM vehicle performance models in AEDT. For the missions of interest, this necessitates operation of AEDT in 'fixed-point flight profile' mode. However, lateral directivity (left, center, right), an AEDT attribute for helicopters, is not supported in fixed-point flight profile mode. If it is determined that lateral directivity is an important factor that must be included for UAM vehicles, then either modification to AEDT, or an alternative to AEDT, will be needed. In the short term, an alternative to AEDT may be needed to assess lateral directivity and metrics beyond those currently supported. In the longer term, new features relevant to UAM vehicles could be incorporated into AEDT.

AAM supports high fidelity directivity, but it too does not include a vehicle performance model and requires the user to define the trajectory and vehicle state parameters. It does, however, permit the user to define explicitly an appropriate noise sphere for each trajectory point. In the future, the automatic sphere selection process in AAM could be improved to allow for UAM specific operational modes.

2.3.2.2 Low Noise Operations Design

Operational planning starts with accurate vehicle noise models. Aside from the gaps in noise modeling and prediction described herein, there is a need to understand the robustness of general noise abatement procedures. It is likely that appropriate guidance may prove to be highly vehicle-configuration dependent, making development of general procedures intractable. One operational solution is to fly over areas with an already high level of background noise (e.g., highways, other transportation systems, etc.) to partially mask the impact of UAM vehicles. There is a need to extend such practices to enable acoustic-based dynamic replanning and integrate acoustic constraints in the air traffic management system, as there will inevitably be many unanticipated obstacles encountered throughout the airspace.

2.4 Recommendations

Further development of validated noise prediction tools is required to support research and development of vehicles and their operations. Specifically:

- System noise prediction tools, developed primarily for assessments of large commercial transports and used more recently for rotorcraft noise assessments, lack fully integrated source noise (including installation effects) prediction methods and advanced propagation tools required for UAM vehicle design and noise reduction technology development. It is recommended that system noise prediction tools be further developed for application to UAM vehicles and made available to the research and industrial communities.

- The introduction of new vehicle configurations employing multiple rotors with potentially different rotational speeds not only generates aperiodic noise, but allows the same vehicle to execute a particular flight condition in more than one manner due to redundant controls. In such cases, current methods to trim the vehicle (including installation effects) and subsequently perform acoustic analyses are inadequate. It is recommended that research be performed to develop conventions on how to handle control redundancies to obtain preferred low-noise trim conditions and to further develop the acoustic tools to handle aperiodic sources.
- Many existing source noise models, including those currently under development, have not been fully validated at UAM scales. Further, there is a need to understand the relative amplitudes of dominant noise sources for archetypal vehicle configurations across the full operational range. It is recommended that prediction models for the highest amplitude noise sources be validated with experimental data for isolated and installed configurations, and that flight test data be acquired to better understand variations under realistic operating conditions, particularly unsteady conditions (e.g., maneuvers and transition). Documentation of some or all of these data should be made publicly available as a comparison data set, as has been done for efforts such as the American Institute of Aeronautics and Astronautics (AIAA) Benchmark Problems for Airframe Noise Computations (BANC) workshops [32].
- Auralization of UAM vehicle noise is important for understanding human response and communicating noise impact, especially in the absence of flight recordings. However, auralization tools that account for source unsteadiness (known to influence the perception of sound) are not well developed. It is recommended that continued development of auralization tools be performed to allow realization of flight operations (including takeoff, forward flight, landing, and transition) for a representative range of vehicle configurations.
- There are a number of potential noise mitigation technologies which appear well suited for application to UAM vehicles; however, many of these are based on laboratory demonstrations and have yet to be matured and demonstrated in flight. It is recommended that a dedicated technology maturation effort be performed on the most promising technologies and that opportunities be sought to evaluate their efficacy in flight.
- Noise prediction tools used for research and noise reduction technology development have limited application early in the design process because of both computational effort and the level of detailed information needed. Sensitivities should be developed and implemented throughout the design tool chain. It is recommended that surrogate or other reduced order model methods be developed so that designers can quickly determine the effects of design changes on noise early in the design process, and that sensitivities be fully implemented to enable optimization of low-noise vehicle designs and operations.
- Tools like AEDT were developed to support mandated community noise assessments of aircraft operations near airports. The current lack of support specifically for UAM vehicles (e.g., performance models), requires analysts to accept the limitations associated with using existing capabilities (e.g., helicopter mode or fixed-point flight profiles in the fixed-wing mode). It is recommended that research be conducted to more fully explore limitations in methods for assessing community noise impact of UAM vehicles in their operational environments, and to generate a software development plan that addresses the limitations of current models over time.
- Noise abatement procedures for piloted and autonomous UAM operations may be difficult to generalize due to the wide variety of UAM vehicle concepts. In the absence of generalized guidance, it is recommended that manufacturers work with appropriate organizations, e.g., the Fly Neighborly / Environmental Working Group, to develop low noise guidance for piloted operations and automated low-noise procedures for autonomous operations that are specific to their products.

3 Ground and Flight Testing

3.1 Introduction

Noise reduction is a critical step to enabling the widespread proliferation and acceptance of aircraft operations around the world. Ground and flight testing have been essential in improving our understanding of acoustic radiation from aircraft and how best to implement noise reduction methods. With a new age in Advanced Air Mobility on the horizon, with UAM as part of it, it is conceivable that many of the existing methods and techniques developed for testing modern fixed and rotary-wing aircraft may need to be modified for application to UAM vehicles.

In this section, the historical motivation for acoustic testing and a high-level assessment of the practices already common across the aeronautics industry will be discussed. Challenges and potential gaps in applying these practices to emerging UAM platforms will be identified, and an outline for the process of developing a future measurement standard will be presented.

3.1.1 Why conduct acoustic testing?

There are many reasons that a manufacturer, government, or research organization might initiate an acoustic test campaign. During the development of new aircraft concepts, the validity of modeling tools being used to design the aircraft is often unknown. Testing is conducted to provide insight into whether these models are capturing the noise sources with enough accuracy to confidently use these tools to guide the design. Alternatively, scaled or component test data can be used to develop empirical or semiempirical models that can be computationally more efficient than physics-based models. Though testing is often conducted first at the model-scale in appropriate wind tunnel or anechoic facilities, more mature designs that will eventually undergo certification typically require full-scale flight testing.

During full-scale testing, unanticipated or undesired noise sources and/or levels are occasionally identified. The test requirements needed to diagnose and mitigate these issues, e.g., phased array measurements, are significantly more involved than those required for certification. However, due to the cost of conducting these larger research endeavors, many aircraft never undergo this level of testing unless a failure to meet certification requirements is foreseen. Understanding how, when, and where noise is generated by an aircraft is critical to understanding how operation of the vehicle will affect communities. Noise certification flight test procedures in use today were largely developed to assess the noise produced by individual aircraft in and around commercial airports. Demonstration of UAM noise reduction technologies and measurement techniques would support the development of new noise regulations.

It is also significant to note that airport noise monitoring systems, and noise monitors and measurement techniques used for other transportation modes, may prove equally helpful and appropriate for UAM vehicles. Data from UAM vehicles are needed to properly assess the appropriateness of such methods. There is also a need to obtain data for subjective evaluation of full scale vehicle sounds. This can be accomplished through sound juries present during tests or evaluated through auralization methods using postprocessed data as discussed in Section 4.2.2.

In the following subsection, some of the more common practices in use today for both research and certification flight testing are highlighted. It is important to remember that some of these practices may be inadequate for widespread operation of UAM in highly populated urban environments. Limitations in current practices will be discussed later in this section.

3.2 Current Practice

The FAA and ICAO currently define aircraft noise certification standards and measurement procedures for separate categories of aircraft. Though the minutiae of the procedures vary from aircraft type to type, the general approach remains the same. An aircraft is flown in controlled flight conditions (takeoff only, flyover only, or takeoff, approach and flyover) over one or more microphones, placed four-feet (1.2 m) above the ground, except as noted below. The acoustic signals are converted to specified noise metric(s), compared to the categories' noise limits, and a determination of the aircraft's noise compliance is made. The existing noise certification standards and procedures that may be applicable to UAM aircraft are given in Table 1.

Table 1: Noise certification standards and procedures that may be applicable to future UAM vehicles.

Annex 16 † Part 36 ‡	Aircraft Type Noise Certification Metric	Procedure
Chap. 8 App. H	Helicopters Noise certification metric: EPNL	Noise is measured with 4 ft. (1.2 m) microphones at three positions (center and ± 150 m) oriented perpendicular to the flight path for three prescribed flight conditions, “approach”, “takeoff” and “flyover”.
Chap. 10 App. G	Propeller-driven airplanes not exceeding 8,618 kg. Noise certification metric: L_{Amax}	Noise is measured with a single inverted ground microphone for a prescribed takeoff condition.
Chap. 11 App. J	Helicopters not exceeding 3,175 kg maximum certificated takeoff mass. Noise certification metric: L_{AE}	Noise is measured with a single 4 ft. (1.2 m) microphone for a prescribed flyover condition.
Chap. 13 App. K	Tiltrotors Noise certification metric: EPNL	Noise is measured with 4 ft. (1.2 m) microphones at the same locations as in App. H. See below for additional details.

† ICAO Annex 16 Vol. I [33] (subsequently referred to as Annex 16)
‡14 CFR, Part 36 [34] (subsequently referred to as Part 36)

The noise certification procedures for tiltrotor aircraft are perhaps the most relevant with respect to UAM aircraft, as there are some similarities between the added degrees of freedom afforded by a tiltrotor and those that will exist for the UAM aircraft. Certification is conducted using approach, takeoff and flyover procedures very similar to those used for helicopter certification. However, the tiltrotor is constrained to operate in VTOL/Conversion mode, where the nacelle angle is held at the position closest to the shallow nacelle angle certified for zero airspeed. This will result in a very different (and likely louder) noise than if the aircraft were operated in “airplane mode.”

Flyover noise measurements similar to those described above most often serve as the basis for constructing vehicle-specific NPD data, per the SAE AIR 1845 standard [35], the AEDT technical manual and other references [36,37]. NPD data may also be generated directly from system noise analyses [38].

Research based methods commonly use large ground arrays (typically flush-mounted or inverted on a ground board). Fixed-wing aircraft testing often includes microphone phased arrays to identify and separate source noises using beamforming techniques, while rotorcraft measurements often deploy arrays distributed over thousands of square feet. Rotorcraft noise processing methods can include backpropagating measured ground noise gathered from steady flyover conditions to map the source noise directivity on a hemisphere surrounding the vehicle [24]. Acoustic source hemispheres, per flight condition, can then be used as a database for empirical or semiempirical noise models. Unsteady test conditions, e.g., maneuvers or any flyover involving acceleration, are often characterized through ground noise footprints using appropriate metrics. In-flight measurements have also been conducted using either quiet chase aircraft, helicopter mounted boom arrays, or even a hot air balloon. Information about the many research efforts in which component or model testing on the ground or in an acoustically treated wind tunnel occurs is widely available.

Any flight test acoustic measurement, whether for certification or research, should respect best practices and constraints on environmental conditions. The test site should have relatively flat terrain and be absent of any excessive sound absorbing materials (e.g., dense foliage, tall grass) or large obstructing bodies (e.g., buildings). Ambient noise levels must be relatively low and free of significant tonal content (particularly for propeller and rotary-wing aircraft). Allowable atmospheric conditions are specified in the standards, and slight variations exist between aircraft categories. Sound pressure levels should be corrected for deviations in environmental conditions.

Aircraft position is measured using photographic scaling or most commonly today, a Global Positioning System (GPS). On-board measurement of the aircraft state and control positions is often made but not always necessary. Synchronization of the aircraft position, state, and acoustic measurements is commonly achieved using GPS and common time signals.

3.3 Gaps

With the advent of UAM, it is anticipated that existing certification and research-based methodologies may need to be adapted or modified. This section details a number of challenges associated with application of current techniques to UAM ground and flight noise testing.

3.3.1 Altered Source Prioritization

Currently, many UAM aircraft configurations are being considered. Each of these aircraft may result in a prioritization of noise sources that is different from those associated with traditional fixed or rotary-wing aircraft. While it is expected that traditional noise sources (see Section 2) such as BVI, thickness noise, loading noise, and gear box noise will be present for many VTOL-type configurations, and airframe-related noise, fan noise, and possibly even jet noise will be present for configurations resembling fixed-wing aircraft, nontraditional aircraft noise sources are expected and are associated with electric and hybrid propulsion systems, multirotor or multipropulsion system configurations, transitional flight states, and the vertiport environment.

Rotor-to-rotor interactions and multirotor-airframe interactions will be different than those for existing aircraft. Multiple independent rotors result in multiple shaft harmonics and multiple tone interactions that can impact structure-borne noise and even result in temporally varying amplitude, or “beating.” Noise sources from ducted rotors, not considered relevant previously, may now become important. Flow recirculation resulting from aircraft operating in the vertiport environment with surfaces near the vehicle may result in new noise sources or modification to noise sources from those previously understood and modeled for traditional aircraft.

Measurement techniques for source identification, separation, and quantification will need to address traditional and nontraditional aircraft noise sources. These sources may occur simultaneously and with priorities that change continuously throughout the flight envelope. These techniques cannot rely on source prioritization assumptions that have been adopted from traditional rotary- and fixed-wing aircraft.

3.3.2 Complex Operating Environment

Considering the more complex operating environments indicated in Section 2.1.2, near- and midfield measurements, often ignored for existing aircraft, may be necessary to quantify the noise environment and will need to capture the impact of scattering and shielding and even possibly the effects of hydrodynamic forcing on nearby structures. These near- and midfield measurements may occur in regions where flow recirculation will have a negative impact on noise measurement sensors. Measurement standardization will be challenged by the large variation in vertiport size and configuration. Urban canyons will have a large variation in length scales, and geometrical features will result in reflection, reverberation, and diffraction, and may act as waveguides.

Measurements are critical for developing and validating multipath propagation tools (see Sections 2.2.1.1 and 2.3.1.1) and noise predictions for these environments. Defining and testing in canonical urban geometries may expedite development. Nonetheless, there will be geometrical differences in the various urban canyons where these aircraft operate that will challenge standardization of measurement-environment requirements. During all segments of the flight envelope, large variations in the mean and temporal background noise levels may occur, and these changes must be quantified and considered in the development of measurement procedures. A standard procedure for characterization of community background soundscapes, such as ANSI/ASA S12.9 Part 1 [39] and Part 2 [40], may be helpful in this regard.

3.3.3 Significant Temporal Variation

For many UAM vehicles, the large number of noise-generating components that comprise the propulsion system may undergo continuous (and independent) changes during takeoff, landing, and overflight when maintaining a prescribed route or counteracting atmospheric turbulence. Some aircraft will likely undergo significant configurational changes which may occur at relatively low altitudes where noise exposure is a concern. Additionally, a wide range of takeoff and landing trajectories may be used, and the noise time histories may be very different for each trajectory. Measurement procedures will need to be developed to capture the relevant range of operational noise.

3.3.4 Variation in Normal Operating Condition

One likely challenge in developing test procedures for UAM is the significant variation in operating state that some configurations enable. Conventional fixed and rotary-wing aircraft have only a limited number of options and so evaluating them is relatively straightforward. For UAM the options are not as well-defined. During takeoff and approach, some UAM vehicles may ascend/descend near vertically, as do many small UAS (sUAS), and transition to/from forward flight, while others could adopt a more traditional low-speed taxi/approach to ascent/descent at a moderate glide slope. In level flight, some configurations may be wing-borne, others rotor-borne, but in all scenarios the UAM aircraft will likely have far greater flexibility in trim state than conventional aircraft. Transition may prove the most challenging flight regime to measure due to the time-dependent nature of the noise that will result from complex tilting procedures of propulsors and/or lifting mechanisms. Depending on the quasisteadiness of the dynamic process, the noise produced by transitioning to forward flight versus higher speed level flight could be significantly different. In both cases, without large ground microphone arrays or simplifying assumptions about the transition procedure, measurement of the full transition will prove challenging. Hover noise can be highly unsteady and may be of importance for UAM vehicles. Methods for repeatable hover noise measurement should be explored. Finally, UAM vehicles will also have to operate for a certain time on the ground near populated environments. Some will do that quickly (start and takeoff) and some will have to wait longer before takeoff (some hybrid-electric vehicles may even want to keep their engines running on the ground). If these conditions are deemed to contribute significantly to community noise, then measurements under these conditions will be needed.

3.3.5 Expanded Directivity Requirements

For conventional aircraft, most acoustic testing is conducted using ground-based microphone arrays. While this has merit for existing helicopters and fixed-wing aircraft operating in and around airports, the anticipated urban environments encountered by UAM may require supplementary measurements at positions elevated above the aircraft to determine the significance of upward radiated noise. The closest example is acoustic testing conducted for fixed and rotary-wing aircraft in which an aircraft is flown near a tower or hot air balloon equipped with microphones. A glider could also be used in the same way in-flight helicopter noise and sonic boom measurements have been made. In the longer term, similar methods may be needed to assess UAM aircraft as they approach and depart from highly populated urban canyons.

3.3.6 "Steady" Flight Condition Variability

For some UAM configurations, it is possible that the repeatability of measurements for the vehicle when operating in the same nominal state may be lower than for current aircraft unless testing is performed in a well-controlled environment where effects of perturbations (such as wind gusts) are systematically assessed. Trim states may have a large time-varying noise component depending on how tight the governing stability and control laws are. Many UAM vehicle concepts may be lightly loaded, which will make them more sensitive to small atmospheric disturbances and require rapid and near constant adjustment of the propulsion system. If RPM-control is employed for multirotor systems, the peak level could be greatly different between a zero-wind condition and flying through even light winds. Moreover, the source noise and its directivity differences associated with gusting winds could be more pronounced. This will likely require more repetition of test conditions, tighter tolerances on aircraft control, more rigorous on-aircraft flight control instrumentation, and possibly longer data records than are currently typical.

3.3.7 "Worst-Case" Operating State

Current fixed and rotary-wing aircraft alter their flight state as a function of gross weight. For many vehicles, the worst-case noise corresponds to conditions met during takeoff (at maximum weight as the propulsors must operate at or near full power), and on approach (in a 'dirty' configuration). For rotorcraft, the 6 degree glideslope defined in Annex 16 Chapter 13 and Part 36 Appendix H was prescribed to assess maximum BVI noise during rotorcraft approach operations. BVI is a highly directional, dominant source of noise under certain conditions (strong dependence on the vehicle's flight path angle) but can be mitigated by adjusting the rate of descent and/or airspeed. For some UAM configurations, a worst-case noise condition may be difficult to define up front. Though sufficiently validated acoustic models may shed some light on the matter, it is likely that test matrices for UAM will be significantly more extensive relative to conventional aircraft, particularly during the early stages of development.

Generally speaking, conditions chosen for acoustic measurements should be representative of operating conditions relevant to the aircraft type. At a minimum, a full flight plan including takeoff, cruise, approach, landing, and any near ground taxiing and ground operations should be considered – each respectively representative of the most common procedures for that given vehicle. This flight plan should also be consistent with the manufacturer's flight manual or preprogrammed routes. Difficulties may arise when defining what truly representative conditions are, particularly with vehicles with excess degrees of freedom. Noise certification and research testing will necessitate a more thorough understanding of the control law definitions. Assurance is needed that typical procedures and control laws employed during testing and certification will not be vastly augmented later so as to realize some performance or cost benefit at the expense of increased noise. Given that the UAM market will evolve at a rapid pace, major operational changes may be necessary at some point in the lifetime of a given vehicle. Manufacturers and regulators should coordinate such procedural modifications to provide an opportunity for appropriate review.

3.3.8 Expanded Flight Envelope Degrees-of-Freedom

Because many UAM vehicle concepts employ a large number of rotor/propulsor systems, obtaining noise measurements for all possible conditions is impractical. Test matrices should be aided by the best available modeling tools but maintain the capacity to identify sensitivity to parameters known to be important inputs to predictive acoustic tools (e.g., tip speeds, advance ratio, thrust coefficients, etc.). Ideally, the noise produced by these aircraft can be parameterized per vehicle class or vehicle type. Measurement procedures should be devised to allow such relationships to be understood. Capturing trends of this nature would also be useful as input to dynamic route planning, potentially optimized to minimize noise in a "global" sense, i.e., minimize noise across a cityscape. In addition, procedures for generating NPDs or characterizing 3D noise emissions will need to be defined that account for the expanded degrees-of-freedom.

3.3.9 Piloted, Semi- and Fully-Autonomous Operation

Because many of the UAM vehicles being proposed involve some level of autonomy, it will be important to consider the influence of this on the noise generated by these aircraft. At the very least, additional instrumentation onboard the aircraft may be required so that the true state of the aircraft is known. In many instances, the instrumentation requirement needed to successfully implement autonomous operation may make this very simple.

3.4 Recommendations

The development of standards, or even a definitive recommendation for standards, is beyond the scope of this white paper. However, several practices commonly used across the aeronautics industry should be strongly considered for near-term testing or future standardization.

- Similar test environment constraints (e.g., ambient levels, benign meteorological conditions) to those discussed in Annex 16 and Part 36, such as precise corrections for navigation error and atmospheric losses, are highly recommended for all tests conducted to measure UAM vehicle noise.
- Significant on-aircraft instrumentation and monitoring of the vehicle state may be required due to varying levels of autonomy and potential increase in degrees-of-freedom of the flight envelope.
- Establishing what is considered the "worst" case or the noisiest mode the vehicle will fly (under automatically controlled Variable Noise Reduction System (VNRS) provisions [41]) will be a challenge, given the large variety of aircraft configurations. Additional work is recommended to define appropriate methods to evaluate acoustic dependence and variability on the vehicle state, and will likely require extensive testing (potentially supplemented with validated models).
- Existing test and certification procedures should not be considered adequate to fully characterize the acoustic impact of a given UAM vehicle. For helicopters, certification measurements have often proved insufficient (due to the sparsity of microphones and number of conditions measured) for use as input into noise prediction models. Therefore, a full assessment of anticipated UAM aircraft flight performance and operational environments is recommended to support the development of any future certification procedures and/or standards.
- Close collaboration between stakeholders (including manufacturers, researchers, and certification authorities) is recommended in the development of new measurement approaches. This is especially important due to the rapid growth of this new industry and class of vehicles.
- Due to the potential importance of noise directed along the horizon and above the aircraft, it is recommended that measurements above the aircraft be investigated to understand their relative importance. Extreme care should be taken to ensure measurements are not corrupted by ground reflections.
- For many decades, four-foot high tripod mounted microphones have been the standard for most certification measurements. This has the unintended consequence of making measurements much more sensitive to local ground conditions, particularly for aircraft noise with dominant tones. Ground plane measurements can offer data to the noise modeling and noise prediction communities that are uncontaminated by reflections (if desired, reflections can be added to ground plane measurements in postprocessing to simulate an above ground level response). Thus, it is recommended to use flush mounted or inverted microphones over a rigid ground plane to enable widespread application of the acquired data.

4 Human Response and Metrics

4.1 Introduction

An understanding of the human response to UAM noise is critical to ensure that UAM vehicle designers focus on design choices, technologies, and operational procedures that maximize the likelihood that these vehicles will be acceptable to the general public. Measures of the noise in the form of metrics that describe a particular response are needed to develop predictive models that, in turn, can be used to inform decision making by vehicle manufacturers and regulators.

4.2 Current Practice

Noise metrics, including those used for noise certification and assessment of community noise, have evolved over time as a result of knowledge gained about human response to noise, measurement and data processing capabilities, metrics usage and interpretation, and the introduction of new noise sources. It should be clear that not all metrics are applicable to all purposes. Further, it can be expected that the evolution of metrics will continue going forward.

In the following, the current practice and how that applies to UAM vehicles will be discussed in terms of metrics that are applicable to vehicle design and those that are used to quantify community noise impact.

4.2.1 Metrics Related to Vehicle Design

Metrics currently used for vehicle design are primarily those related to noise certification. Noise certification requirements [33,34] reflect a compromise between the available technology and cost, and therefore may not fully reflect acoustic factors related to human response. Further, current certification metrics were developed many years ago based on an earlier understanding of psychoacoustics, and when data acquisition and processing capabilities were more limited. Metrics currently used by regulatory agencies for noise certification that may be applicable to UAM vehicles (see Table 1) include:

- The maximum A-weighted sound pressure level, slow response, relative to 20μPa, designated by L_{Amax} (dBA). The frequency weighting in L_A adjusts the actual decibel level to a scale matching the level perceived by the human ear, according to a single equal loudness contour. The duration of the event does not influence L_{Amax}.
- The A-weighted sound exposure level, designated by L_{AE} (dBA). L_{AE} takes into account amplitude, duration, and spectral content through A-weighting. All else being equal, a doubling of duration increases L_{AE} by 3 dBA.
- The effective perceived noise level. The EPNL metric takes into account amplitude, duration, and spectral content, and also includes a penalty for tones.

Detailed information on the above and other aircraft noise metrics can be found in Ref. [42].

4.2.2 Metrics Related to Community Noise

4.2.2.1 Integrated Noise Exposure and Annoyance

The most common measure of community noise impact is long-term (daily, annual) integrated noise exposure. Integrated noise exposure metrics are typically based on the A-weighted equivalent continuous sound level, designated by L_{Aeq}. These measures include the day-night average sound level (DNL), designated by L_{dn}, the community noise equivalent level (CNEL), designated by L_{den}, and the equivalent continuous sound level over a time period T, designed by $L_{Aeq,T}$. Calculation of integrated noise exposure is based on the equal-energy hypothesis, which postulates that the number, level, and duration of noise events are interchangeable contributors to the integrated level, as long as the total energy remains constant. For example, a DNL of 65 dB can be produced at a certain location by a single event with an SEL of 114 dBA, or by 100 events, each with an SEL of 94 dBA.

AEDT and similar tools are used to estimate integrated long-term noise exposure of aircraft operations for communities that experience aircraft noise, see Section 2.2.2. Additionally, some airports have installed noise monitors in neighboring communities to measure noise exposure. The number of people living within the boundaries of specific noise contours are sometimes reported as a means to quantify community aircraft noise exposure. In the U.S., DNL and CNEL (California) are used to determine land use compatibility, per CFR Part 150 [43], and for compliance with NEPA. In the calculation of long-term aircraft noise exposure, consideration is not typically given to background noise levels from existing natural and/or human-made noise sources.

A relationship between noise exposure (dose) and average annoyance (response) for transportation noise sources was originally established by Schultz [44] (the "Schultz curve") and was later updated [13] (the "updated Schultz curve" or "FICON curve") based on analysis of additional data by Fidell et al. [45]. These relationships originally did not differentiate between aircraft and other transportation noise sources. Subsequently, it was found that aircraft noise is more annoying than road and rail noise [46]. Based on this finding, an aircraft noise specific dose-response relationship was standardized in Ref. [47]. The FICON dose-response relationship was recently revisited in an FAA sponsored study conducted at 20 U.S. airports [48], the results of which are expected to be released in late 2020.

4.2.2.2 Other Considerations

Alternative Measures of Noise Exposure

L_{Aeq} -based metrics as main predictors of annoyance to long-term noise exposure may be limited by the fact that A-weighted levels do not account for tonality or temporal effects. This suggests that decibel penalties may need to be applied to integrated energy for UAM applications, e.g., as incorporated in the tone-corrected perceived noise level used to calculate EPNL. Alternative metrics based on psychoacoustics have also shown to be more accurate predictors of annoyance over L_{Aeq} -based metrics, e.g., those used in the domain of product sound quality [49].

Alternative Measures of Response

Measures of response other than annoyance have been used in the U.S. as a basis of policy, for purposes other than land use planning and compliance with NEPA. Specifically, audibility has been used by the National Park Service (NPS) in response to legislation to substantially restore the "natural quiet" in the Grand Canyon National Park [50]. According to the NPS, substantial restoration is achieved when more than half of the park experiences no audible aircraft for 75-100% of the day.

Indoor versus Outdoor Response

Existing community noise regulations, for example in [43], are often based on target criteria for maximum average indoor noise exposure, which is strongly influenced by building transmission loss. The assumption that airport noise of 65 L_{dn} is compatible with residential land use is based on a target of 45 L_{dn} in the residence, i.e., 20 dB of transmission loss. In many cases, the transmission loss is less than that, e.g., in communities where houses are less robust or where windows are commonly left open. The U.S. Environmental Protection Agency (EPA) predicts a 10-12 dB differential in noise level reduction (NLR) for open windows versus closed windows, and a 3-5 dB NLR based on construction of typical residential structures in warm and cold climates [51]. Best practices for determining interior noise levels in homes near airports, due to aircraft flyovers, include a recommendation that the aircraft spectrum being used be representative of the airport's fleet mix [52]. That recommendation would presumably hold for UAM noise operating in environments away from airports.

Vibration and rattle of building structures from aircraft noise are known to potentially contribute to human response indoors. Vibration may be caused by either structural transmission (e.g., a vehicle landing on a vertiport on the roof of a building) or airborne loading (e.g., building façades exposed to high-level noise). Rattle is a nonlinear phenomenon associated with loose items (e.g., dishes) and windows. The consideration of vibration and rattle is applicable to residential and commercial constructions, including vertiports. It typically results from low frequency energy and is often associated with sonic boom, large rotorcraft main rotor sound and occasionally with high-level jet noise [53,54]. When present, corrections to applicable metrics are sometimes applied to account for short-term [55] and long-term [56] exposure. In the case of rotorcraft, no statistically significant relationship has been found between annoyance due to in-home vibration and rattle, and annoyance due to noise level alone [8].

In outdoor settings, the benefits of transmission loss from building structures are lost. This is not unique to UAM aircraft noise, and a balanced approach is taken to manage that noise, see Section 1.3. One element of that approach is land use planning and management, and one aspect of that is vertiport siting. Introduction of a vertiport near an already noisy transportation source, e.g., a freeway entrance cloverleaf, will likely be less intrusive than its introduction in a residential area. The degree of intrusion will, in part, depend on how different the character of the noise source is from the ambient at a particular time of day.

Non-Acoustic Factors

As with any annoyance model based only on acoustic metrics, there is no consideration given to non-acoustic factors. Non-acoustic factors are generally understood to include things like fear of the aircraft crashing, attitudes toward the noisemaker, and "noise sensitivity" [57]. These have all been shown to be important contributors to annoyance in numerous studies. "Virtual noise" [58] refers to the notion that the annoyance is higher than the "measured" noise level would indicate. It is also conjectured that noise is a trigger for the additional negative response.

Other Adverse Effects of Aviation Noise

In addition to annoyance, the adverse effects of aircraft noise on sleep, academic performance of children, and incidence of cardiovascular disease of people living near airports, are summarized in Ref. [59]. There is no indication at present that suggests these effects would be different for UAM noise.

Communicating Noise Impact

Sound demonstrations (e.g., using "auralization" methods that provide a veridical experience) have been shown to be effective tools for communicating noise impact to communities in a more meaningful way than simply reporting sound exposure levels. There is current work in placing both synthesized and processed real vehicle recordings in an immersive soundscape that represents the existing or future "soundscape" of a community. This is of interest both to vehicle designers wishing to optimize acoustic acceptability, and potential operators who want to demonstrate a potential change in acoustic exposure in a community.

4.3 Gaps

4.3.1 Metrics Related to Vehicle Design

Design strategies that seek to minimize noise from UAM vehicles are hindered by a lack of measured data. A majority of proposed vehicles are still under development and, during that stage, acoustic signatures are often considered proprietary. As of this writing, the very limited publicly available acoustic signature data indicate that UAM acoustic signatures will be significantly different in character, both temporally and spectrally, than those from existing vehicle classes. The development of validated predictive models of human response to UAM noise requires such data. Improvements in the fidelity of conceptual UAM vehicle noise predictions and auralizations allow a starting point for developing predictive models, and simultaneously offer a means to simulate the noise resulting from different aircraft design strategies.

At this time, there have been no published reports of psychoacoustic tests conducted to understand human response to UAM vehicle noise. The applicability of recent annoyance studies of other Advanced Air Mobility vehicles, including sUAS [60] and proposed short haul distributed electric propulsion aircraft [61], to UAM is unclear. Differences in response (if any) to UAM noise versus that of helicopters and other fixed-wing aircraft have not been established. Further psychoacoustic research is therefore needed to determine the magnitude of any differences and consequently the applicability of metrics and predictive models, over the wide range of operating conditions expected of UAM vehicles.

In the near term, UAM noise certification is expected to adopt existing requirements. In the longer term, the noise certification process may change to reflect knowledge gained from the above type of psychoacoustic testing.

4.3.1.1 Perception-Influenced Design for Noise

Just as current noise certification regulations do not (nor were they intended to) reflect all aspects of human response, there is no reason to believe that future regulations will do so. Therefore, in addition to meeting noise certification requirements, a low noise design process may also incorporate measures that minimize other forms of human response, e.g., audibility.

Perception-influenced design (PID) is the process by which an engineering design accounts for human perception. By this definition, design of vehicles to meet noise certification requirements already constitutes a form of PID, as L_{Amax}, L_{AE}, and EPNL are based on human perception. Acoustic design that only considers the noise certification metric becomes inadequate when the characteristics of the noise are not reflected by the metric, e.g., the impulsive noise of helicopters is not explicitly reflected in SEL or EPNL. In these cases, alternative metrics or models of human response can be used in conjunction with noise certification metrics to design vehicles that both meet the noise certification requirement and achieve some desirable effect on human perception. Reference [62] provides several examples of this approach.

Psychoacoustic testing is required, particularly for novel sounds, to determine which alternative measure(s) best describes the targeted response. The palette of metrics includes those adapted from certification metrics (e.g., replacing the tone penalty in EPNL, based on 1/3-octave band data, with one based on narrowband data), sound quality metrics [63] (e.g., loudness, sharpness, tonality, roughness, fluctuation strength, and impulsiveness), and audibility metrics (e.g., *d*-prime, which is the sensitivity index for audibility originating from signal detection theory [64]). It is often the case that dependencies are found between the targeted response and several metrics, in which case a model of the response may be developed using constituent metrics as model parameters. For example, the psychoacoustic annoyance model [63] is a function of the sound quality metrics for loudness, sharpness, roughness, fluctuation strength, and optionally [65] tonality.

For PID to be successfully applied to UAM vehicle acoustic design, development of metrics and models that are easily incorporated as design constraints is needed. Further, verification and standardization of metrics and models that can be applied by any interested party are needed.

4.3.2 Metrics Related to Community Noise

4.3.2.1 Integrated Noise Exposure and Annoyance

The effectiveness of L_{Aeq}-based metrics as predictors of annoyance to long-term UAM vehicle noise exposure is unknown. That question cannot be completely answered until annoyance data are acquired in real communities subjected to real UAM vehicle noise, including some assessment of the variance between communities. Laboratory tests cannot serve as a substitute for community studies because the relationship (if any) between annoyance to short-term (laboratory) exposure and long-term (community) exposure is unknown. Laboratory studies, however, can help inform how different the annoyance to short-term exposure of UAM vehicle noise is from that of other aircraft noise sources. Any identified differences could point to the need for other metrics, e.g., one based on EPNL, or a different level of a current metric, e.g., a penalty on DNL for UAM vehicle noise. In the interim, assessments may be made to determine the sensitivity of noise exposure estimates to changes in the metric or to its level.

The frequency of occurrence of UAM vehicle operations (in some scenarios up to two per minute) is predicted to be far greater than fixed-wing aircraft and conventional rotorcraft operations, but less persistent than road traffic (for which L_{Aeq}-based metrics work fairly well). It is not known how well the equal-energy hypothesis will hold up in such conditions. Other acoustic factors, e.g., changes to the characteristics of the existing soundscape, and difficulty to localize (such as when urban canyons are present), may also influence annoyance.

4.3.2.2 Other Considerations

Alternative Measures of Noise Exposure

It is not known how annoyance (or other measures of response, see below) to UAM vehicle noise might be dependent on alternative measures of exposure (i.e., those not based on L_{Aeq}). These measures include loudness-level-weighted sound exposure level (LLSEL), number of events above a threshold noise level (NANL), time above a threshold level (TAL), time audible relative to ambient, sensitivity index (*d*-prime) and partial specific loudness for different time-varying vehicle and background noise.

Alternative Measures of Response

There exists a continuum of human response levels from audibility to noticeability to annoyance. Both natural and human-made background (ambient) noise are dependent on the location, the time of day, the day of the week, and seasonal variations. Audibility refers to the level at which the signal (UAM vehicle noise) can first be heard in the presence of a masker (ambient noise) by either an individual or some percentage of the population. The essential idea is that if UAM vehicle noise is not audible, it will not be annoying (based on acoustic factors alone). Several audibility models have been developed over the years [66,67] and applied to aircraft noise, but these models have yet to be validated with UAM vehicle noise and representative ambient noise. Without doing so, an understanding of how UAM audibility changes with changing signal and ambient conditions (in terms of amplitude, temporal, and spectral characteristics) will be lacking.

At a higher amplitude, the signal becomes noticeable, i.e., the level at which an audible sound is recognized as intrusive. Some proponents of UAM operations suggest that the threshold of noticeability could serve as a surrogate for acceptability. Like audibility, noticeability is a function of the amplitude, temporal and spectral characteristics of the signal and masker. However, noticeability is also a function of what a person is doing at the time the sound is recognized as being intrusive, so it may be more difficult to define in an absolute sense. Simple measures are sometimes used to specify noticeability, e.g., noticeability of aircraft noise in the Grand Canyon National Park is several dB above ambient. Since noticeability criteria would vary between communities on daily, weekly, and seasonal bases, establishment of a national policy would not be feasible.

Indoor versus Outdoor Response

Since UAM vehicles will operate in proximity to people, outdoor noise may be high compared to other aircraft noise, or become more noticeable due to reflections off buildings or other features within an urban environment. The significance of these interactions is currently unknown.

Building vibrations and rattle are typically caused by low frequency noise and are known to affect human response indoors. It is not known if UAM vehicle noise will contain enough low frequency energy for this to be an issue.

Non-Acoustic Factors

The role of non-acoustic factors in human response to UAM operations is unknown. Such factors might differ from those found to be important for existing aircraft, including rotorcraft.

4.4 Recommendations

Further development of metrics and validated predictive models of human response is needed to inform decision making by UAM vehicle manufacturers and regulators. Specifically:

- Measured and simulated vehicle acoustic data are needed to support subjective response studies for metric and predictive model development. It is recommended that efforts be made to acquire/generate such data (inclusive of metadata, e.g., vehicle location with respect to the receiver), and to make those data available for research purposes.
- Standardized processes for measuring and cataloging ambient noise are needed to facilitate its use in human subject testing. It is recommended that these processes be developed, inclusive of metadata documenting location, time of day, measurement equipment, etc.
- Community noise studies of early entrants are needed to assess the effectiveness of L_{Aeq}-based metrics as predictors of annoyance to long-term UAM vehicle noise. That may not be possible for some time. In the interim, it is recommended that laboratory studies be performed to help inform how different the annoyance to short-term exposure of UAM vehicle noise is from that of existing aircraft noise sources. Assessments can then be made to determine the sensitivity of noise exposure estimates to changes in the metric or to its level.
- Validated models for audibility, noticeability, and annoyance to UAM aircraft noise are needed to assess their utility for assessing community noise impact. It is recommended that such models be developed and validated over a wide range of operating conditions and demand scenarios, taking into account a representative range of ambient/background conditions.
- The assumption that airport noise of 65 L_{dn} is compatible with residential land use is based on a target of 45 L_{dn} inside the residence. It is recommended that transmission of UAM noise through residential (and commercial structures) be quantified in order to evaluate the 20 dB loss assumed by current land use compatibility guidelines.
- It is recommended that measures of human response be developed and used as constraints in perception-influenced design. Ideally, such measures would be easily calculated and include sensitivities.
- Communicating community noise impact using integrated metrics, specifically L_{dn}, is often difficult because the metric bears little relation to how individuals experience noise. According to the recent FICAN research review [68] of aviation noise issues, supplemental metrics are those that supplement L_{dn} in “communicating effects as opposed to supplementing L_{dn} in assessing significance in the context of impact analysis.” It is recommended that a comprehensive evaluation of supplemental metrics be performed in terms of their effectiveness and readiness for communicating the effects of UAM vehicle noise.
- It is likely that different communities may react differently to the introduction of UAM vehicle noise, e.g., those communities that are regularly exposed to aircraft noise versus those that are not. It is recommended that a laboratory test campaign be used to explore differences in perception of UAM vehicle noise between communities, e.g., a round-robin test, so that future policy decisions are based on data representing a wide range of environments.

5 Regulation and Policy

5.1 Introduction

Electric propulsion, distributed lift, and autonomous flight technologies have emerged inspiring new UAM vehicle type designs. For this market to be successful, industry must overcome several barriers to entry including community concerns on safety, privacy, noise, etc., and meeting regulation requirements.

Currently, the FAA authorizes small UAS weighing no more than 55 pounds to operate commercially under 14 CFR Part 107 [69], and package delivery operations under CFR Part 135. Pertinent to Part 107, the FAA allows limited operations outside the rule through a special waiver request program. The FAA is currently promulgating a new rule that furthers the Part 107 rule to allow small UAS operation over people and at night under certain conditions. Since 2017, the FAA's UAS Integration Pilot Program (IPP) has brought state, local, and tribal governments together with private sector entities, such as UAS operators and manufacturers, to test and evaluate the integration of civil and public UAS operations into the national airspace system. The IPP program does not limit the UAS weight to be below 55 pounds.

As it relates to noise certification of UAM designs, the U.S. noise certification regulations are found in Title 14 of the Code of Federal Regulations, Part 36 [34], which has specified standards for airplanes, rotorcraft, and tiltrotors that takeoff and land primarily at airports or helipad environments. Most foreign countries follow the international standards in Annex 16 [33]. Part 36 and Annex 16 are considered equivalent since both use the same approved procedures. The current regulations have been developed for conventional fixed-wing aircraft and rotorcraft types. While some of the existing noise certification methods and procedures may be still applicable to some UAM designs, new certification procedures may be needed to better represent the unique features of UAM vehicles. More details will be discussed in Section 5.2.

All U.S. federal agencies have to comply with NEPA when proposing major federal actions. The FAA has established DNL 65 dB as the threshold of significant aircraft noise exposure (FAA Order 1050.1F [70]), below which residential land use is normally compatible and noise impacts are generally not considered significant under NEPA. The FAA defines a significant noise impact under NEPA when the action would increase noise by DNL 1.5 dB or more for a noise sensitive area that is exposed to noise at or above the DNL 65 dB noise exposure level, or that will be exposed at or above the DNL 65 dB level due to a DNL 1.5 dB or greater increase, when compared to the no action alternative for the same timeframe. For example, an increase from DNL 65.5 dB to 67 dB is considered a significant impact, as is an increase from DNL 63.5 dB to 65 dB. For air traffic airspace and procedure actions, change-of-exposure tables and maps at population centers are provided to identify where noise will change by the following specified amounts:

- For DNL 65 dB and higher: ± 1.5 dB
- For DNL 60 dB to < 65 dB: ± 3 dB[*]
- For DNL 46 dB to < 60 dB: ± 5 dB[*]

Specifics and details are needed in NEPA studies such as knowledge of aircraft types, noise source characteristics, flight profiles, local weather and terrain conditions, and baseline and alternative traffic operations. Proper capabilities in prediction tools such as AEDT need to be developed.

Community engagement is an important element in aviation noise management, particularly when a change is introduced in the aviation system. Community engagement is a process of taking part in dialogue and collaboration with communities affected by the aviation changes. Although community engagement does not guarantee outcomes that satisfy everyone, decisions that consider community input are more likely to reflect the collective public interests, receive broader community acceptance, and experience fewer issues associated with implementing changes in the aviation system.

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[*] The FAA refers to noise changes meeting these criteria as "reportable."

5.2 Current Practice

The primary means of controlling aircraft noise at the source is through noise certification requirements.

Part 36 applies to airplanes, helicopters, and tiltrotors of conventional designs. They are configured with fixed-wings, fixed-rotors, or tilting proprotors to provide lift. Primary flight controls employ movable control surfaces for fixed-wing aircraft and rotor orientation changes for rotorcraft (a combination of the two schemes is used for tiltrotors). Noise level is primarily dependent on mass and power of the aircraft: noise level increases as weight and thrust are increased.

Current noise certification categories are based on types of aircraft and propulsion, and weight. Aircraft designed and used for agricultural and firefighting are excepted and not subject to noise certification per Part 36 (§36.1583).

There seems to be a misconception in the industry regarding the applicability of Part 36 to UAM aircraft. Because these vehicles are considered aircraft, they are subject to the noise certification and testing requirements of Part 36. Currently, Part 36 has effectively no minimum weight requirement and has no requirement for an onboard pilot, so technically all UAM aircraft need to be noise-certificated.

It is expected that the UAM vehicle will be heavier than most UAS vehicles and will be configured for vertical lift with capabilities to transition into efficient forward flight. It is also expected that initial UAM noise certification activities will be based on the current Part 36 requirements. As experience and data are gained, more tailored certification procedures will be adopted that better represent the unique noise characteristics and operational features of UAM vehicles. It will likely be necessary for the FAA to develop noise certification standards for these aircraft.

In the event that a UAM vehicle fails to fit into one of the current noise certification categories, the FAA still has the statutory mandate re. Title 49, U.S. Code §44715 to control aircraft noise for the public welfare and to prescribe regulations. In that case, and as an interim solution, an issue paper is often developed to provide requirements and specifications for subject aircraft as a rule of particular applicability. Existing regulatory elements of noise certification are used where appropriate – with modifications, if needed, for the specific application. Further, the issue paper may require additional testing to address the unique characteristics of a particular aircraft design, configuration, propulsion system, flight dynamics, and typical or likely mission profiles, including proximity to the community. The additional flight testing (with no limits imposed) is needed to provide supplemental data that can be used to predict noise in communities or to support development of future regulations. By requiring these data collections, the FAA expects to gain experience and understanding to develop general noise certification procedures and specifications in the future. For now, approval of the package is part of the rule in order to obtain a type certificate (TC). Once the FAA noise specialists have agreed on the procedures, with management and applicant endorsement, the issue paper will be published in the Federal Register as a “Rule of Particular Applicability”, which means it only applies to a particular aircraft.

Aircraft can incorporate variable systems, primarily intended to reduce the takeoff/approach noise. Current categories of aircraft have limited flexibility in specifications regarding flight test conditions through the integration of an automated VNRS. Unlike regular certification, that can have different flight paths for certification and operation, the VNRS takeoff and landing flight paths in certification should be relevant to day-to-day operations. Current regulatory guidance specifies that the Takeoff flight test procedure is generally accepted for use of VNRS. It may be necessary to expand this guidance to include Flyover and Approach procedures for UAM vehicle purposes. Supplemental operations are being voluntarily included in certification flight tests to address some potential concerns, e.g., level flyovers in addition to takeoffs for small propeller aircraft (Part 36 Appendix G). The “Best-fit” approach is under consideration, which will evaluate each new application for the most appropriate category.

5.2.1 Working with International Partners

The ICAO is the specialized United Nations agency that works with Member States and aviation stakeholders to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. These SARPs and policies are used by ICAO Member States to ensure that their local civil aviation operations and regulations conform to global norms. ICAO's Committee on Aviation Environmental Protection (CAEP) is a technical committee of the ICAO Council focused on creating environmental SARPs and guidance. ICAO CAEP Working Group 1 – Noise (WG1) is the forum for technical aviation noise related work.

CAEP is currently investigating the status of UAS/RPAS (Remotely-Piloted Aircraft Systems) noise certification. The scope of this work includes UAS/RPAS, electric/hybrid aircraft, air taxis, eVTOL, etc. In recent WG1 discussions, members received Information Papers (IP) from the European Union Aviation Safety Agency (EASA) and the FAA on research and development of national standards related to new entrants. The IP highlighted the unique qualities of UAS/UAM vehicle noise in terms of broader operability and physical noise characteristics, and noted that many of the concerns regarding UAS/UAM noise in the community, including noise certification, can only be addressed by obtaining UAS/UAM aircraft noise data. Data collected from small UAS are expected to aid in the understanding of noise concerns related to larger UAM vehicles, but collection of noise data from these larger aircraft will be needed as well. NPD data sets will be needed to conduct noise assessments in AEDT.

The ICAO has informed member states that an amendment to Annex 8 (Airworthiness of Aircraft) covering RPAS will be sent for consultation by ICAO Member States prior to its adoption. The ICAO has also informed member states that the RPAS panel will be focused on the development of Annex 6 Amendments (Operations), which may present the need for further coordination with WG1 due to the references to Annex 16 contained in Annex 6.

Summary of Recent ICAO Recommendations

A steady increase in the electrification of aircraft systems, research on electrical propulsion, and investments in electric or hybrid aircraft designs have been noted. The electrification of general aviation or recreational aircraft; business and regional aircraft; large commercial aircraft; and vertical takeoff and landing aircraft is attracting funding. Some new concepts are hybrid-electric designs, while others are fully powered by batteries. Some companies target an entry into service date between 2020 and 2030, and some are already commercially available. Four eVTOL projects had their first flights in 2019 (Lilium, City Airbus, Boeing Aurora eVTOL, and Bye Aerospace Sun Flyer 2).

There are currently no specific ICAO environmental standards in Annex 16 to cover such aircraft types. ICAO is monitoring the developments around these new entrants, and which specific SARPs will need to be developed.

Summary of Recent European Commission (EC) Decisions

In a recent meeting with the EC members and industry in Brussels, the EC stated that the European Union (EU) primary regulations (EASA Basic Regulation) and secondary high-level regulations are in place. However, the certification regulations are still the missing piece, and are needed for security, safety, and privacy (and environmental) concerns. They are looking to put in place certification regulations for UAS over 20 kg.

Later in the meeting, it was announced that the EC is coordinating with other authorities on UAS, and working with the ICAO and the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) on RPAS. The fact that they stated that they are working with the ICAO implies that they will address environmental requirements.

The EC stated that implementation of regulations for UAS will be at the EU member state National Aviation Authority (NAA) level, and that even if the EC creates the overarching requirements for UAS, each NAA may create different environmental requirements depending on the national tolerance to UAS in the areas of noise and privacy. The EC would like to get out ahead of the NAAs and provide unified requirements for UAS operations (including environmental). It is understood that allowing the NAAs to make individual requirements without coordination will be undesirable.

The EC also stated that the EC/EASA is willing to consider adopting industry standards if they are available for any aspect of UAS certification or implementation, and are willing to work with standards organizations and other airworthiness authorities. EASA has yet to grant a TC on a UAS as of this writing.

The two major aviation authorities, the FAA and EASA, are managing TC applications of the new entrants in a similar manner for noise. Both organizations manage the applications on a case-by-case basis by adopting the Part 36/Annex 16 procedures as required.

5.3 Gaps

5.3.1 Lack of Data to Support Noise Certification

For fixed-wing aircraft, the noise certification procedures in Part 36 are developed for conventional aircraft that takeoff from and/or land on runways. Even for rotorcraft, the noise certification procedures in Part 36 contain only level flight (and takeoff and landing for Part 36 Appendix H). There is no hover mode test in the current Part 36. Further, numerous details prescribed in the testing procedure such as flight altitude, variations allowed in the vehicle speed and in trajectories and positions, adjustment for blade tip speed, wind speed limits, etc., are developed for conventional aircraft as well. Some of them may be applicable to UAM, some may not be. Data are needed to understand those issues.

Data are also needed to understand proper noise limits for UAM vehicle operations. There is a limited understanding of how communities will react to UAM vehicle noise with unfamiliar characteristics. While UAM noise levels may be lower than those produced by conventional aircraft, their novel operating mode, distinguished frequency characteristics, and time-varying signatures may be more annoying and, as experienced with helicopters, fear and privacy concerns may increase annoyance even at lower noise levels (see Section 4).

5.3.2 Lack of Guidance for Vertiport Planning

There is a gap regarding guidance for the compatibility planning of future UAM vertiports. During the 1980s, the Helicopter Association International advised the FAA on voluntary guidance for siting of new heliports. AC 150/5020-2 (1983) [71] resulted from this work, recommending suitable distances between a new heliport and its community based on a change in ambient noise level produced by operations. A revision was prepared in 1987 but was never adopted, and the 1983 AC was canceled in 1988.

Future UAM vertiports are expected to host up to a thousand aircraft per day that are generally quieter than helicopters. Guidance is needed on identification of vertiport locations that would be compatible with existing or planned land use, and on the assessment of environmental impact due to noise at proposed UAM vertiport locations. Part of the challenge in such development hinges on the roles of FAA versus local jurisdiction when it comes to understanding “federal action” in the context of vertiports.

5.3.3 Lack of Clarity on Boundaries of Responsibilities in Community Engagement

While the rapid pace of development of UAM vehicles is exciting, premature deployment without sufficient local community engagement and risk management can have a devastating impact on the future. The general public needs to have confidence in safety and to develop a realistic expectation of noise scenarios associated with new air vehicles and flight operations. Airport operators have shown that keeping people informed about changes in air traffic can reduce the number of complaints and promotes tolerance by the community. Thus, community engagement is essential to inform people about UAM and how it would impact their lives. This includes both the benefits and the concerns about noise, safety and privacy. As with cases of helicopter noise, UAM aircraft noise issues will expand beyond the airport environs, and may extend across multiple jurisdictions and municipalities, which could make it difficult to coordinate community outreach and decision making on noise mitigation. Similar to issues the FAA has experienced with helicopter noise concerns on the U.S. east and west coasts, there is no centralized group to support the FAA with dissemination of information and to work through possible solutions. In addition, it may be a challenge to track the flight trajectories of individual flights. All of these issues make addressing and handling noise and nuisance concerns more difficult, but also make it more important that the FAA has a plan in place to prevent noise from becoming a barrier issue for industry. It is important to note that while the U.S. Congress has provided the FAA with exclusive authority to regulate aviation safety, the efficiency of the navigable airspace, and air traffic control, etc., state and local governments have regulatory authority over aircraft landing sites, which involves local control of land and zoning. Laws traditionally related to state and local police authority – including land use, zoning, privacy, and law enforcement operations – generally are not subject to federal regulation. So this means that while cities and municipalities are not permitted to have their own rules or regulations governing the operation of aircraft, they may generally determine the location of aircraft landing sites through their land use powers.

5.4 Recommendations

- At the national level, the FAA, in collaboration with other agencies and the industry, should address certification, standards, and environmental reporting for UAM noise before these vehicles enter service. This is needed so that local communities are not panicked into the establishment of ordinances that will both limit growth of the market and potentially create operationally restricted zones.
- A key part of the collaboration is to share data and experience. Industries, as innovative as they are, should be more proactive in approaching regulators to help them understand vehicle designs, noise characteristics, operating modes, etc., and to share relevant data. Regulators, as programmatic as they are, should help the industry to understand the regulation process and policies, and to identify specific data needs to bridge gaps in standards and procedures. R&D programs, technical committees, and workshops are some of the venues that such collaborations can take place, in addition to direct communications.
- Collect more data in the field through R&D programs and leverage data from manufacturers. The data would not only help to support noise certification of UAM vehicles, but also to assist the development and validation of noise prediction capability for noise impact analyses and to identify approaches and best practices for quiet aircraft designs and for quiet aircraft operations.
- Regulators and policy makers should work to clarify the boundaries of responsibilities in managing UAM noise, and support development of guidance for vertiport planning regarding both location identification and environmental assessment at the proposed locations.
- Develop a strategy and framework for community engagement before UAM noise concerns arise. Being prepared to address local community noise concerns early in the process will be critical to success for this market. Initial flight operations should not come as a surprise to the affected community. Modern tools such as virtual reality with auralization could provide effective ways to inform and engage the public.

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Appendix A List of Acronyms

AAM	Advanced Acoustic Model
AEDT	Aviation Environmental Design Tool
AEE	FAA Office of Aviation Environment and Energy
AIAA	American Institute of Aeronautics and Astronautics
ANOPP2	2nd Generation Aircraft Noise Prediction Program
BAI	Blade-Airframe Interaction
BANC	Benchmark Problems for Airframe Noise Computations
BVI	Blade-Vortex Interaction
BWI	Blade-Wake Interaction
CA	Comprehensive Analysis
CAEP	ICAO Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CNEL	Community Noise Equivalent Level
CSD	Computational Structural Dynamics
DNL	Day-Night Average Sound Level
EAM	Emerging Aviation Markets
EASA	European Union Aviation Safety Agency
EC	European Commission
ECAC	European Civil Aviation Conference
eCTOL	Electric Conventional Takeoff and Landing
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level
EPNdB	EPNL (in decibels)
EU	European Union
eVTOL	Electric Vertical Takeoff and Landing
F1A	Farassat's Formulation 1A
FAA	Federal Aviation Administration
FICON	Federal Interagency Committee on Noise
FWH	Ffowcs Williams-Hawkings
FWI	Fuselage-Wake Interaction
GPS	Global Positioning System
HALE	High Altitude Long Endurance

ICAO	International Civil Aviation Organization
IP	Information Papers
IPP	FAA’s UAS Integration Pilot Program
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LBM	Lattice Boltzmann Method
NAA	National Aviation Authority
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NLR	Noise Level Reduction
NPD	Noise Power Distance
NPS	National Park Service
PAA	Propulsion Airframe Aeroacoustic
PID	Perception-Influenced Design
PNL	Perceived Noise Level
RPAS	Remotely-Piloted Aircraft Systems
RPM	Revolutions per Minute
RVLT	NASA Revolutionary Vertical Lift Technology Project
SARP	Standards and Recommended Practices
SEL	Sound Exposure Level
sUAS	Small UAS
STOL	Short Takeoff and Landing
TC	Type Certificate
TIN	Turbulence Interaction Noise
TWG	Technical Working Group
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UNWG	UAM Noise Working Group
VNRS	Variable Noise Reduction Systems
VTOL	Vertical Takeoff and Landing
WG1	ICAO CAEP Working Group 1 – Noise

Appendix B List of Symbols

L	Sound pressure level (dB)
L_{A}	A-weighted sound pressure level (dBA)
L_{AE}	A-weighted sound exposure level (dBA)
L_{Aeq}	Equivalent continuous sound level (dBA)
$L_{Aeq,T}$	Equivalent continuous sound level over time period T(dBA)
L_{den}	Community noise equivalent level (dBA)
L_{dn}	Day-night average sound level (dBA)

Appendix C UAM Noise Working Group

C.1 Background and Purpose

The Urban Air Mobility Noise Working Group (UNWG) was created in October 2018, following a UAM Noise Exploratory Meeting held in April 2018. At the Exploratory Meeting, there was strong consensus, among a diverse group of approximately 70 representatives from government, industry, and academia, that semiannual meetings should occur on the topic of UAM noise, with NASA serving as a coordinating entity. The primary function of the UNWG is to coordinate technical work addressing the high-level goals (see Section 1.4.1). Most of the work occurs between the meetings through the UNWG Executive Committee and its four subgroups (see Appendix C.2). Focused talks and progress toward the goals are reported at the semiannual meetings for review and discussion by all participants. Since its inception, participation at the semiannual meetings has increased to approximately 125 subject matter experts from a multitude of organizations in the U.S. and abroad (see Appendix C.3). Participation in the UNWG is open to interested parties.

C.2 Organization

The UNWG is organized into four subgroups with the following co-leads:

1) Tools and Technologies
   Leads: Doug Boyd (NASA Langley) and Paul Bent (Boeing)

2) Ground and Flight Testing
   Leads: Brenda Henderson (NASA Glenn), Kyle Pascioni (NASA Langley), and Juliet Page (U.S. DOT Volpe)

3) Human Response and Metrics
   Leads: Siddhartha Krishnamurthy (NASA Langley) and David Josephson (Josephson Engineering)

4) Regulation and Policy
   Leads: Bill He (FAA) and Royce Snider (Bell Flight)

The UNWG Executive Committee, comprised of the subgroup leads, Dennis Huff (NASA Glenn) and Stephen Rizzi (NASA Langley), coordinates the activities across subgroups.

C.3 Participating Organizations

(As of 2019)

3DS
ADSE
Airbus
Arup
ATAC
ATA Engineering
Aurora Flight Sciences
Bell
Beta Technologies
Blue Ridge Research
Boeing
Collins Aerospace
Continuum Dynamics, Inc.
Dallas/Ft. Worth Airport

Embraer
EMS Brüel & Kjaer
FAA Office of Environment and Energy
Florida State University
GE Aviation
Georgia Institute of Technology
Great Lakes Sound & Vibration
Hanley Innovations
Hexcel
HMMH
Honeywell
Joby Aviation
John Wood Group PLC
Josephson Engineering
Lilium
Lockheed Martin
NASA (Ames, Glenn, and Langley Research Centers, and Armstrong Flight Research Center)
National Institute of Aerospace
NLR (Royal Netherlands Aerospace Center)
Northrop Grumman
Old Dominion University
OptiNav
Pennsylvania State University
Porsche Engineering
Purdue University
Sikorsky
Stanford University
Techsburg
Terrafugia
Uber Technologies
University of Cambridge
University of Maryland
University of Salford
University of Southampton
University of Texas at Austin
University of Toledo
U.S. Air Force Research Laboratory
U.S. Army Futures Command
U.S. Army Research Laboratory
UTRC
Volpe National Transportation System Center
Wichita State University

Appendix D Rotational Noise Prediction Methods Applicable to UAM

Isolated Sources

Deterministic (Tonal) Rotational Sources

The subsets of solutions to the FWH equation are typically used for the prediction of deterministic sources. The acoustic pressure at a set of observers may be determined using either a permeable or impermeable source surface. In the former, flow passes through the surface, inside of which contains both surface and volumetric acoustic sources. The permeable surface is often used as either a surface surrounding the blades and rotating with them, or as a nonrotating surface enclosing the entire rotor or vehicle, see Figure 8. Though this method is relatively simple to implement, spurious signals can arise if acoustic sources traverse across the surface. The impermeable or solid surface formulation allows for surface acoustic sources only, eliminating the generation of artificial spurious signals. Fortunately, UAM configurations generally have low rotor/propeller tip Mach numbers, so some volumetric sources, e.g., high speed impulsive noise, do not typically occur. However, spurious signals can also arise when vortices pass through the permeable surface [72]. Therefore, the impermeable formulation is expected to be effective in most cases. In the following, the impermeable formulation is considered. In particular, Farassat's Formulation 1A (F1A) [73] is often used for this purpose.

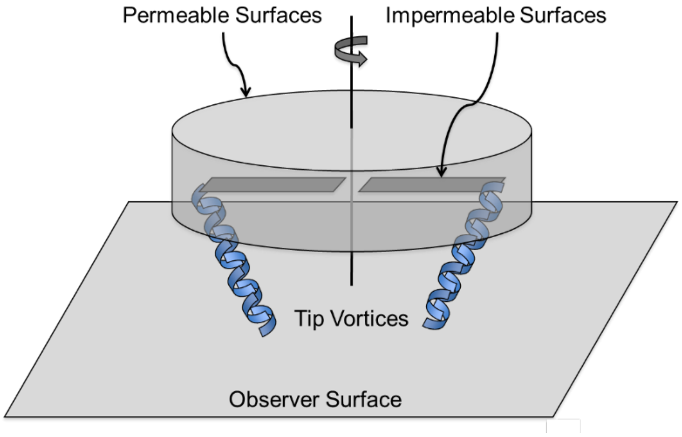

Figure 8: Depiction of permeable and impermeable surfaces for FW-H calculation.

"Thickness noise" is related to the air displaced by a body that is in motion relative to an observer. Conceptually, thickness noise relates directly to the blade geometry and blade motion. Given accurate blade geometry and blade motion, thickness noise is accurately predicted. Computation of thickness noise from full surface blade geometry and blade motion is relatively fast. For a designer, an even faster, yet still quite accurate, method comes from "compact thickness" models [74-76]. These compact thickness models provide a computation that is about an order of magnitude faster than the full surface computation, but that is still accurate as long as there is no violation of the compactness assumptions. Both the full surface and compact methods are commonly available and are in routine use.

"Loading noise" is related to the aerodynamic forces acting on a surface. Effectively, loading noise can be from a stationary source (with respect to the observer) with unsteady loading, from a steady loading on a surface that is moving relative to an observer, or from a combination of both. An accurate acoustic prediction of loading noise requires that accurate aerodynamic data and surface motion are provided to the acoustic solver. For a rotor/propeller, the aerodynamics and the blade motion are almost inseparable; they both strongly affect each other. For a noncompact loading noise calculation, CFD and CA are often coupled to obtain loading data over the surface of the blade. A "loose coupling method" generally passes aerodynamic and blade motion data between codes at time intervals (usually at some interval that is a multiple of the blade passage or rotor revolution), often with an assumption of periodicity imposed on the solution. This approach works well when the motion is periodic or can be considered quasisteady (or quasiperiodic), e.g., for maneuvers when the maneuver time scale is long relative to the rotational time scale of the rotor. For maneuvers where the time scale of the maneuver is on the time scale of the rotation of the rotor, a "tight coupling method" has been used in the past. Tight coupling uses the method of passing aerodynamic and structural data between codes at every time step of the prediction. However, this method is very computationally expensive. For aperiodic cases, a general loose coupling method is not available; however, a tight coupling method could be used. Such a method, however, would be even more computationally expensive than previous implementations on a single rotor due to the multirotor application. For a compact loading noise calculation, lifting line loading data along the span of the blade may be computed using CA.

Loading noise may be i) steady periodic, e.g., a propeller with uniform inflow, ii) unsteady periodic, e.g., a propeller at an angle of attack or in a pusher configuration mounted aft of a pylon, or iii) unsteady aperiodic. If the source is aperiodic, then the amount of blade loading data needed for calculation of the acoustic pressure at a far field observer (using F1A) is large and is dictated by the extent of the retarded time relative to the observer location. If the source is steady periodic or unsteady periodic, the amount of blade loading data can be reduced to that of a single blade passage or a single revolution, respectively. The combination of multiple rotors/propellers has the added complication that the summed pressure at the receiver may be aperiodic if the rotors/propellers are asynchronous or operating at different rotational rates from one another. In this case, propagation to a ground observer using a frequency domain approach becomes problematic, see Section 2.2.1.

A particular form of impulsive loading noise is BVI noise. In BVI noise, the tip vortex from a blade interacts with another blade such that the interaction is parallel. This interaction can occur on an intrarotor and/or interrotor manner. BVI noise for conventional helicopters can be dominant in descending flight, but can also be found in forward/level flight. For helicopter main rotors, when examining measured data, BVI noise is often treated as unsteady periodic through synchronous time averaging of loading data across multiple revolutions (as is typical of other measured data processing). However, in prediction methods, BVI is often treated as periodic loading noise as are other deterministic loading noise sources.

Nondeterministic (Broadband) Sources

There are some first principle methods to compute rotor/propeller self noise at this time, but they are currently computationally expensive or impractical for vehicle design, e.g., some very promising first principles methods capable of computing most sources of relevant noise include a LBM hybridized with a Very Large Eddy Simulation. Instead, rotor/propeller self noise is typically computed using a semiempirical model based on airfoil section data and acoustic measurements made in the late 1980s [30]. This model suits rotor cases well when accurate information related to the boundary layer, section velocities, and section angles of attack is available. It currently lacks generality with respect to items such as multiple rotors and general cambered airfoil shapes. Because of the low rotor/propeller tip speeds of UAM aircraft, self noise is expected to be a significant contributor to the total system noise.

BWI noise generally occurs as the result of turbulence associated with a tip vortex or wake structure interacting with a blade. An example of BWI noise is a tip vortex interacting with a blade in a perpendicular manner. Because this is associated with turbulence, it is a nondeterministic source. There are no general first principle methods currently available to compute this noise source. There have been semiempirical methods examined, but the methods developed were not generalized.

TIN is due to blade-turbulence interaction, in which atmospheric turbulence presents an unsteady inflow, giving rise to unsteady aperiodic loading noise and (to a lesser extent) modifying broadband self noise.

Installed Sources

Aerodynamic Effects

Many UAM vehicles under consideration have propulsion system components in proximity to one another and/or to the airframe. The former may generate BVI and BWI noise, see Figure 5. BWI involves the turbulence field associated with (and outside the potential core of) the rotor wake system. The turbulence around the wake interacts with the blade loading and generates noise. Empirical modeling is currently the standard; however, this modeling is infrequent due to lack of model generality and lack of experimental data to generalize the models. There is experimental evidence of interaction between rotors that affects broadband noise, and this is not currently modeled in most methods. The current interpretation is that the rotors are close enough that there is a strong wake induced influence of one rotor on another. This influence changes the conditions of each rotor, thereby changing the broadband noise from each. With the anticipated multirotor configurations, with many rotors in proximity, this BWI effect will be more dominant than in conventional rotorcraft.

Several aerodynamic effects can also result from installation of a rotating propulsion source near the airframe. These include, but are not limited to:

- unsteady loading on a propeller in a wake deficit region, e.g., a pusher configuration.
- the steady potential flow around the airframe, e.g., a propeller near the leading edge of the wing
- recirculation of downwash, e.g., fountain flow.
- unsteady loading on the airframe making it another loading noise source, e.g., horizontal strut near lifting rotors in a lift plus cruise configuration.
- ducts in edgewise flight in which separated flow is ingested by the rotor, creating a source of unsteady aperiodic loading noise.

The above aerodynamic interactions affect tonal and broadband noise generation to various degrees, depending on the configuration. The accuracy of the noise prediction is highly dependent on the turbulence modeling used by the flow solver. Consequently, the computational burden is high, making aerodynamic effects (associated with interactional aerodynamics) on noise generation difficult to address in general.

Acoustics Effects

Because the acoustics considered here are likely linear, the effects of all sources may be summed at the observer independently. However, the effect that a body has on the acoustic field from another body is neglected in that instance. Effectively the sound propagates to the observer as if no other bodies are present. To account for the effects of one body in the acoustic field on another body, scattering methods (accounting for reflections and shielding) can be used. These methods compute an additional acoustic field for a body to negate the field (from other sources) that would pass through itself. This additional acoustic field is then added to the observer to account for scattering effects. Time domain and frequency domain methods are available for computing the effect. A suppression map may be subsequently applied to the isolated source. Scattering methods are not routinely used in the rotorcraft community because of the limited effect scattering has for conventional rotorcraft. For UAM vehicles, however, scattering may be a significant effect.

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14. ABSTRACT
In 2018, NASA formed an Urban Air Mobility Noise Working Group (UNWG) to assemble noise experts from industry, universities and government agencies to identify, discuss, and address urban air mobility (UAM) noise issues. This paper presents a set of high-level goals intended to address barriers associated with UAM noise that may hamper their entry into service. It summarizes the current practice, identifies gaps in the current practice, and makes recommendations to address the gaps to achieve the high-level goals in four areas of interest: Tools and Technologies, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy.

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