Environmental Research and Consultancy Department

Emerging Aircraft Technologies and their potential noise impacts

CAP 1766

Published by the Civil Aviation Authority, 2019
Civil Aviation Authority,
Aviation House,
Gatwick Airport South,
West Sussex,
RH6 0YR.

First published March 2019

The work reported herein was carried out under a Letter of Agreement placed in March 2018 by the Department for Transport. Any views expressed are not necessarily those of the Secretary of State for Transport.

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Introduction

DfT is developing a new Aviation Strategy[1] to look at aviation's challenges with the aim "to achieve a safe, secure and sustainable aviation sector that meets the needs of consumers and of a global, outward-looking Britain" and will set out the long-term direction for aviation policy making to 2050. As part of the preparation of the Aviation Strategy consultations, DfT has requested that CAA undertakes the noise analysis for this work.

In view of the new Aviation Strategy, the objective of this report is to review the potential noise impacts of future technologies in the Aviation Strategy. This includes a literature review of the noise associated with the development of electric aircraft (Chapter 2), supersonic aircraft (Chapter 3), drones (Chapter 4) and spaceplanes (Chapter 5). It discusses and proposes an interim approach to the management of their noise impacts in the early years of their operations.

The work includes:

- Literature review of potential technology designs;
- Literature review of noise modelling and noise measurements related to the future technologies;
- Recommendation of interim approach/regulation to address early days of technology update;
- Overview of other environmental impacts that may need further consideration.

Appendix A covers a description of the noise sources discussed in this report.

[1] "Aviation Strategy - Developing an aviation strategy to support industry in delivering improvements for passengers, the environment and our country.", Department for transport, 2018.

Chapter 2
Electric Aircraft

Background

Electric aircraft form an important component of achieving greenhouse gas emissions, air quality and noise exposure targets for aviation as they can reduce dependence on fossil fuels and allow for independent use of aircraft power generator and power propulsion, which could facilitate different aircraft designs such as Blended Wing Body (BWB) and Distributed Electric Power (DEP) that may also contribute towards reducing aviation noise.

At the international level, one of ICAO's main priorities and one of the Organization's key environmental goals is to limit or reduce the number of people affected by significant aircraft noise[2]. The main overarching policy on aircraft noise is the Balanced Approach to Aircraft Noise Management and includes four main elements: reduction of noise at source, land-use planning and management; noise abatement operational procedures; and operating restrictions. As part of noise reduction as a source, ICAO sets noise limits for new aircraft and currently distinguishes between different aircraft types (e.g. light and heavy propeller aeroplanes, helicopters) and power plants (propeller and jet aeroplanes). Historic fleet evolution has achieved great progress over the years using conventional aircraft designs and gas-turbine (jet) engines. Electric powered aircraft are considered as part of the effort to reduce noise and would potentially need to go through the same aeroplane noise certification procedures as jet and propeller powered aeroplanes and comply with the same noise certification limits. Although only small electric powered aircraft are available at present, ICAO is monitoring and promoting the certification of electric flight concepts. Unmanned Aircraft Systems are covered in Chapter 5. Manned air taxis in the electric aeroplane category (i.e. not capable of vertical take-off) that would be expected to comply with ICAO propeller aeroplane noise certification requirements are covered in this chapter.

In Europe, the European Commission's Flight Path 2050 vision aims to achieve a reduction in carbon dioxide emissions of 60%, nitrogen oxide pollution of 90% and noise reduction of 75% by 2050 and this has been, in part, the motivation for some manufactures to embark on electric aircraft development programmes[3].

In the UK, cleaner, greener flight is being encouraged through industry and government investment and as part of that the government announced investments in support of

2 "On Board – A Sustainable Future", Environmental Report, ICAO, 2016.

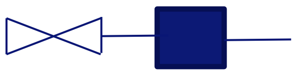
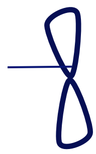
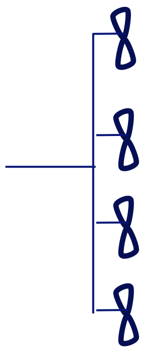
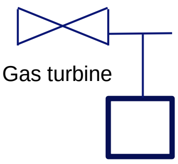
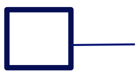
3 "Flightpath 2050 Europe's Vision for Aviation", ISBN 978-92-79-19724-6, European Union, 2011.

cleaner and greener hybrid aircraft during the 2018 Farnborough International Airshow[4]. A major beneficiary of the latest research and development funding is the demonstrator project E-Fan X (partnership between Siemens, Airbus and Rolls-Royce). The E-Fan X project aims to test a hybrid-electric propulsion system in a medium aircraft and expected to be ready by 2020.

Technologies designs

There are three main technology types being considered as future electric aircraft from a power generation perspective, including turbo-electric, hybrid-electric and electric aircraft, as presented in Figure 1. Noise from air taxis is covered in this report as part of a Fully Electric design if take-off is horizontal and under Unmanned Aircraft Systems (Chapter 4) if vertical take-off.

Figure 1: Main Electric Aircraft technology types

Technology Type	Power	Propulsion
(a) Turbo-electric	 Turbo-shaft; Electric Power generator	 Conventional combined propulsion system  Distributed propulsion system
(b) Hybrid-electric	 Gas turbine; Battery	
(c) Fully Electric	 Battery	

Turbo-electric aircraft: In a Turbo-electric aircraft, turboshaft engines are used to drive an electrical power generator to provide electricity to motors, driving the propulsors that in

[4] https://www.gov.uk/government/news/lift-off-for-electric-planes-new-funding-for-green-revolution-in-uk-civil-aerospace

turn drive the fan[5]. This arrangement provides flexibility of design and can be used for BWB and DEP.

Hybrid-electric aircraft: In a hybrid electric aircraft there are two power sources, a gas turbine and a battery (or fuel cell) and both can be used to provide power to the fan[6]. In this report, this technology type is considered to have similar designs as conventional aircraft, although in the literature sometimes the term Hybrid-electric includes Turbo-electrics.

Fully electric aircraft: In a fully electric aircraft the power is provided only by batteries, fuel cells or energy collectors. The power is distributed to electric motors that drive the fans[7].

From a propulsion perspective, there are different solutions varying from single fan and ducted fan to distributed propulsion (multiple fans). They can be used with different types of power generation, but overall full electrification will bring flexibility in design to allow for improved aerodynamics by distributing the motors into many locations on the aircraft, enabling multiple smaller motors and further integration between airframe and propulsion systems.

For comparison with the electric technologies, a conventional aircraft with turbo-fan engines is considered for qualitative analysis.

Weight

Considerations about weight are important on aircraft, as they determine other characteristics of a design, such as wing size (area), propulsion thrust/power and the weight of the power supply itself. The power supply weight will also impact range, cost of operation and available payload. Weight considerations are taken into consideration in this work, as the weight of the power supply in electric planes differs from conventional planes.

Turbo-electric aircraft are in general designed to be lighter than conventional aircraft and lighter than fully electric aircraft as the turbo generator is optimised to produce electrical power rather than propulsive thrust. In a hybrid-electric aircraft, fuel burn will allow for fuel mass reduction during flight. The weight of this configuration is comparable with the weight of an equivalent conventional aircraft. In a fully electric aircraft, the weight is a function of batteries and propulsion system. Due to use of batteries, the weight of the batteries

[5] J.L. Felder, “Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid-Wing Body Aircraft”, NASA.

[6] B.J.Brelje, “Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches”, Progress in Aerospace Sciences, 2018.

[7] B. Łukasik and W. Wiśniowski, “FULL-ELECTRIC, HYBRID AND TURBO-ELECTRIC TECHNOLOGIES FOR FUTURE AIRCRAFT PROPULSION SYSTEMS”, Journal of Powertrain and transport, Vol, 23, no. 4, 2016.

remains the same throughout the flight. A recent study[8] showed that the weight of fully electric aircraft is higher than for conventional turbofan aircraft and higher than hybrid-electric or turbo electric aircraft due to current battery technology. Battery technology is continuously improving and hence the weight difference is likely to diminish in the future. Technology needs and progress[9], on energy density of batteries compared with kerosene is presented.

Beyond the weight of the power system, the weight of the aircraft is also influenced by the weight of the propulsion system. Therefore, turbo-electric and fully electric aircraft have wider opportunities for the reduction of weight of their propulsion systems given that their configuration facilitate the use of multiple electric motors for DEP configurations.

Thrust & Power

The thrust requirements are a function of drag, mass and number of propulsors. The requirements for thrust and power for hybrid-electric aircraft in general will be like the requirements for conventional aircraft, i.e. take-off runway length, ability to operate with one engine inoperative and time to cruise altitude. Given the higher weight, a fully electric aircraft would require higher thrust and power than hybrid-electrics and conventional aircraft or may have poorer climb performance, with potential adverse noise implications.

Power supply weight

In hybrid-electric configurations, kerosene will be consumed during the flight and therefore the landing mass will be less than the take-off mass. In contrast, for a fully electric aircraft the landing mass will be the same as the take-off mass and it will be higher than for other propulsions configurations. Higher mass during the landing approach will lead to higher thrust requirements and potentially lead to higher noise emission.

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8 A.P. Synodinos et all, “Preliminary noise assessment of aircraft with distributed electric propulsion”, 2018 AIAA/CEAS Aeroacoustics Conference, 2018.

9 Andreas W. Schäfer et al, “Technological, economic and environmental prospects of all-electric aircraft”, Nature Energy, 10 December 2018. https://doi.org/10.1038/s41560-018-0294-x

Noise sources, modelling and measurement

Noise at Source

In a turbo-electric aircraft, the main sources of noise are the turbo-shaft engine, the electric generator and the propulsors[10] (motor and fan). The motor noise contribution is considered small compared to the other sources.

In a hybrid-electric aircraft, the main sources of noise are from the gas turbine, fan, electric motor and airframe.

In a fully electric aircraft, the main noise sources come from battery systems, the electric propulsors (motor and fan) and the airframe. The battery systems noise is considered negligible. During take-off, propulsion noise is dominant and although the electric aircraft weight is higher, the noise is expected to be reduced because of the higher mass flow and lower exhaust speed of the electric propulsors compared with conventional turbofan engines. The larger electric propulsors, could however, lead to increased fan inlet noise. During landing approach, higher aircraft mass will drive a larger wing and/or higher lift flap system that may increase airframe noise. The increase in drag associated with heavier aircraft and higher lift flap system will also require extra power which will increase electric propulsors noise. Preliminary research on electric motor noise for aircraft propulsion applications have been made and are predicted to be low compared to other propulsion noise sources[11]. This research also shows that the electric propulsors' weight is reduced when the number of propulsors increases, as the weight increases in a quadratic way with the fan diameter.

Noise Modelling and Measurements

From a noise modelling perspective, current modelling tools are expected to be able to consider electric aircraft, however adjustments will be required to reflect the aircraft performance and noise characteristics of electric aircraft. A framework for predicting noise characteristics of electric aircraft has been created[12] and could be used once tested to decompose the noise characteristics from each aircraft component.

Initial noise measurements are being undertaken for small electric aircraft and for scale models of commercial aircraft types. There is still a clear need to undertake noise

[10] A.P. Synodinos et all, "Noise Assessment of Aircraft with Distributed electric propulsion using a new noise estimation framework", 24th International Congress on Sound and Vibration, 2017.

[11] D. Huff et all, "Motor Noise for Electric Powered Aircraft, 22nd AIAA/CEAS Aeroacoustics Conference, 2016.

[12] A. Synodinos et all, "Framework for Predicting Noise–Power–Distance Curves for Novel Aircraft Designs", Journal of Aircraft, Vol. 55, No. 2, March–April, 2018.

measurements of the full scale commercial electric planes once they are available to fully understand their noise characteristics and any different source noise directivity considerations that may need to be used for noise modelling.

Noise exposure and annoyance

Work is progressing to determine the noise exposure from electric aircraft. It is still unknown whether the noise exposure from electric aircraft will be an improvement from conventional turbofan powered aircraft. According to Synodinos[13] preliminary modelling results, electric aircraft are likely to reduce residential noise exposure around airports at take-off (for the same thrust the jet velocity and jet noise are lower due to higher airflow through propulsors) and increase noise levels during approach (due to the energy density of current batteries). Noise exposure will vary depending on the number of propulsors (motors and fans), decreasing as the number of propulsors increases, as propulsion weight varies with fan diameter. Also, because electric planes are predicted to be heavier, they are expected to climb at a slower rate after take-off compared with conventional aircraft and this may have an additional effect on noise exposure on the ground, offsetting some of the benefits of reduced source noise emission.

Electric propulsion is expected to alter the frequency spectrum of the sound emission. Fan noise emission, which is made of both broadband (a wide range of frequencies) and pure tone noise will likely dominate the sound emission. According to NASA[14], the combination of multiple propellers has the potential to alter the relationships currently being used between noise exposure and annoyance due to their combined amplitude and phase modulation.

Qualitative analysis

Range of potential noise impacts identified

Some predictions [15] show that medium commercial aircraft operating short-haul flights could be electrified in the early 2030s, whereas long-haul aircraft are not anticipated to be electrified until at least 2050. Noise levels of electric commercial aircraft may be higher than their kerosene fuelled equivalents if battery technology improvements driving reduction of weight in fully electric aircraft are not realised. The main improvements driving

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[13] A.P. Synodinos et all, "Preliminary noise assessment of aircraft with distributed electric propulsion", 2018 AIAA/CEAS Aeroacoustics Conference, 2018.

[14] S. Rizzi et all, "Annoyance to Noise Produced by a Distributed Electric Propulsion High-Lift System", NASA, 2018.

[15] "Aircraft Electrical Propulsion – Onwards and Upwards", Think:Act, Roland Berger, July 2018.

weight reduction are battery power density and the use of superconductors for power distribution. A quantitative assessment would be required to assess if the noise reduction from hybrid-electrics and subsequent increase in noise from the introduction of fully-electric would have an impact on forecast trends for airport noise exposure.

Electric air taxis are foreseen to operate in predominantly urban environments, and thus may not contribute significantly to noise exposure in vicinity of many airports, however, whilst quieter in terms of single event noise emission, their proximity to dense urban environments, number of units and lower flying altitude, could lead to the development of an additional urban noise source necessitating appropriate management.

Next Steps

The analysis undertaken highlights that based on medium term battery technology, hybrid-electric aircraft offer the most potential for medium haul aircraft and that fully-electric aircraft are more likely to be considered only for short haul operations, until battery energy density improves.

A quantitative assumption of fully electric aircraft entering into the market around 2035 at, say, a rate of say 3% per year would be required to identify if noise exposure might increase by 2050, depending on different battery technology scenarios, however, there remains considerable uncertainty regarding the introduction date and rate of uptake.

Results from demonstrator projects such as the E-Fan X will give more information on the hybrid-electric propulsion system potential for larger regional aircraft by 2020, which will also allow for full-scale noise measurements to be undertaken and facilitate development of aircraft noise calculation models.

In terms of manned air taxi electric aeroplanes, it is presumed that until specific noise standards are created the current ICAO Annex 16 Chapter 10 light propeller noise certification requirements and maximum levels apply. Since the Chapter 10 standard does not specify the power plant that drives the propeller, nor does it have a minimum mass applicable, the maximum flyover level being 70dB LAmax for propeller aeroplanes with a mass below 570kg.

From a modelling perspective, in the medium term, planned developments of the noise calculation method conforming to ECAC Document 29[16] and ICAO Doc 9911[17], should enable the prediction of noise levels for hybrid-electric and all electric aircraft.

[16] "ECAC Document 29 - Report on Standard Method of Computing Noise Contours around Civil Airports", 4th Edition, ECAC, December 2016.

[17] "ICAO Document 9911 - Recommended Method for Computing Noise Contours around Airports", ICAO, January 2018.

Other environmental impacts that may need further consideration

A faster introduction of electric aircraft may be desirable for the reduction of greenhouse gas (GHG) emissions and further research and investment into noise reduction may be required to ensure that noise reduction advances at the same rate as GHG reduction.

Chapter 3

Supersonic Aircraft

Background

New supersonic civil aircraft are expected to enter into service in the mid-2020s, starting with the business jet market, followed by small airliners targeting time sensitive business-class passengers.

Spike, one of the new manufactures[18], says aerospace manufacturers aiming to produce supersonic civil aircraft[19], predicts that the opportunity for supersonic flights may be up to 13 million passengers per year worldwide by 2025 out of a global market in excess of 5 billion passengers. These opportunities will only be delivered if the requirements for safety, operational requirements and environmental performance can be achieved. It is likely that environmental requirements will be the most important criteria and noise in particular[20] . There are two noise aspects related to the re-introduction of supersonic aircraft operations. The first is to address the impacts on communities around airports of noise from supersonic aircraft landing and taking off and the second is the potential to permit supersonic flight over land, if noise from the sonic boom associated with supersonic flight can be mitigated to acceptable levels.

International noise standards

From an international perspective, ICAO Annex 16 Vol. 1 landing and take-off noise standards[21] are currently defined only for subsonic jet aeroplanes, therefore no standards exist for supersonic aeroplanes. ICAO continues to make progress on development of a landing and take-off supersonic jet aeroplane noise standard and the UK is playing an active role in this work. [22]

18 http://www.spikeaerospace.com/spike-aerospace-predicts-supersonic-market-exceeds-13-million-annually

19 http://www.spikeaerospace.com/spike-aerospace-predicts-supersonic-market-exceeds-13-million-annually

20 H. Welge et all, “N+2 Supersonic Concept Development and Systems Integration”, NASA/CR-2010-216842, NASA, 2010.

21 “Environmental Protection”, ICAO Annex 16 to the Convention on International Civil Aviation, Vol.1 Aircraft Noise, 2017.

22 Supersonic Aircraft Noise Standards Development”, ICAO, 2018.

Technologies design

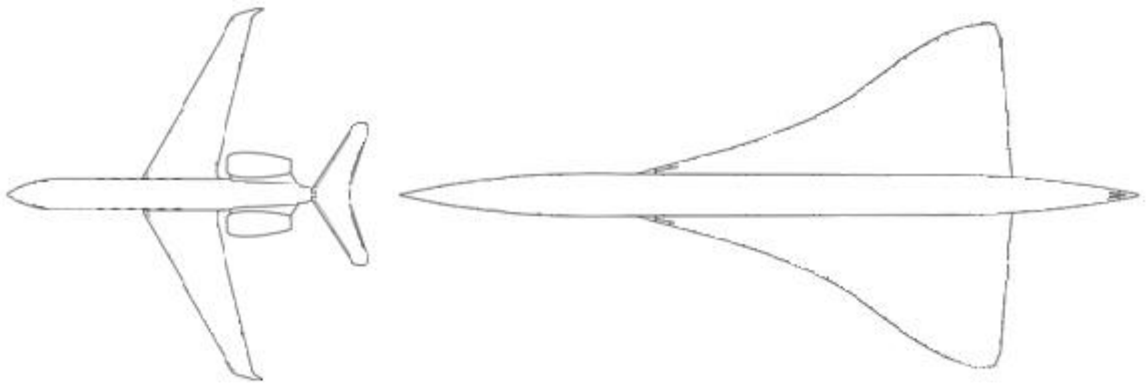
The current proposed supersonic designs are being developed with the aims of reducing both environmental impacts and operational costs. To achieve these objectives, different configurations are being considered, some of which are designed for only over-water supersonic flight, producing a conventional sonic boom, and some are specially shaped to minimise the sonic boom generated with the aim of supersonic flight over land. Table 2 gives an overview of the types of supersonic aeroplane, depending on their speed of operation.

Table 2: Types of supersonic aircraft and typical civil operations

Type of Supersonic	Operation	Speed	Power sources	Noise Sources
Supersonic – Conventional Boom	Airliner	>Mach 1	Jet	Jet noise, sonic boom
Supersonic – Low Boom	Business jet, airliner	>Mach 1	Jet	Jet noise, reduced sonic boom

Flight at supersonic speed generates much higher drag, that no longer increases uniformly with increasing flight speed, but instead, peaks in the transonic region[23] around Mach 1.1. To minimise supersonic drag, supersonic aircraft are designed with less slender wings, with minimised frontal and increased fuselage length to diameter ratio, as illustrated in Figure 1. Supersonic flight will generate tow sonic booms, the first sonic associated with the front part of the aircraft and the second associated with wing, fuselage and engines.

Figure 1: Comparison of fuselage and wing shape for (a) subsonic business jet and (b) supersonic conventional airliner.



(a) (b)

[23] The transonic flight region is where flight speeds are close to the speed of sound, i.e. just below and just above the speed of sound.

Developments focused on further improvements in aerodynamic efficiency are being undertaken[24]. To minimise the first sonic boom, associated with the front part of the aircraft, the canopy and fuselage need to be considered. To minimise the second shock wave is harder as there are many contributions such as wing, fuselage and engines. The configurations analysed in studies by NASA show that if the engine is integrated above the aircraft and wing it is possible to achieve lower boom conditions, however these configurations tend to have higher drag then other designs. [25] Despite the improvements being undertaken to reduce drag, the power to weight ratio is still higher when compared with subsonic aircraft, which will increase the fuel requirements, increasing emissions in comparison with subsonic airplanes. [26]

Noise sources, modelling and measurement

Noise at Source

The main sources of noise from supersonic aeroplanes are jet noise and sonic boom.

The biggest noise source during take-off of supersonic aircraft is jet noise[27]. As current supersonic aircraft generate more drag than conventional aircraft, they require much higher thrust to achieve and maintain supersonic flight. To achieve the high levels of thrust, lower bypass engines are used, which have higher jet exhaust velocities compared with modern subsonic aircraft, during both cruising flight and take-off. The higher jet exhaust velocities during take-off generate higher noise at take-off.

Opportunities to reduce jet noise, whilst meeting the thrust and jet exhaust velocity requirements for supersonic flight, are limited with existing engine technology. A NASA study[21] shows some opportunities to reduce noise in supersonic aircraft including fan noise reduction, noise suppression and engine core noise improvement opportunities.

There are not many proven technologies to reduce jet exhaust velocities whilst providing the thrust necessary for supersonic flight. The Dassault HiSAC concept (EU research project) considered a variable bypass ratio engine as a means of reducing jet exhaust

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[24] A. Sriram et all, “Aerodynamic Shape Optimisation of Transonic and Supersonic Aircraft configurations”, 43rd Aerospace Sciences Meeting, 2005.

[25] H. R. Welge et all, “N+2 Supersonic Concept Development and Systems Integration”, NASA/CR-2010-216842, NASA, 2010.

[26] J.Morgensten et all, “Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2018 to 2020 Period Phase I Final Report”, NASA/CR—2013-217820, NASA, 2013.

[27] B. Henderson et all, “Jet Noise Research at NASA”, BiblioGov, 2013.

velocity at take-off, however, no such engine concept has ever been built or put into service, as it presents significant weight and mechanical complexity challenges.[28]

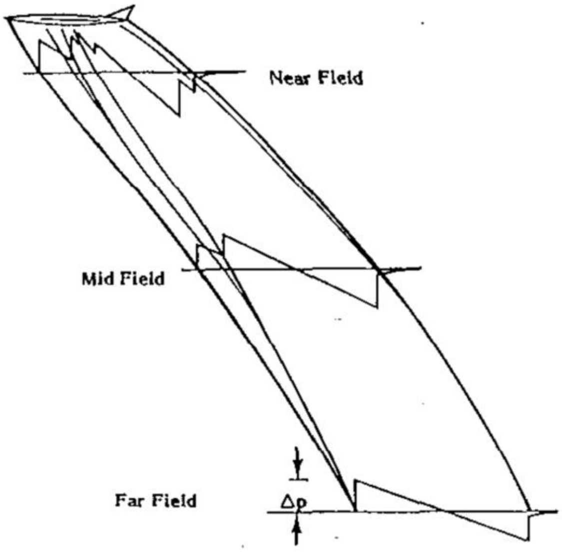
Recent NASA analysis has focused on possible jet nozzle treatments for noise reduction, but their initial results shows that the noise reduction will be limited and modified landing and take-off procedures may be needed to comply with current subsonic noise standards[29]. For instance, supersonic aeroplanes do not require full power at take-off, therefore one option is to reduce take-off thrust immediately after lift-off to reduce noise. Other options include allowing the aircraft to accelerate sooner after to take-off, facilitating more efficient climb given that supersonic aircraft are more aerodynamically efficient (have lower drag) at higher speeds.

Normally noise from aircraft in cruising flight is not an environmental problem. However, flight at supersonic speeds causes a shock wave to be created that propagates to the ground from cruising flight, even at altitudes at or above 50,000 feet. A conventionally shaped supersonic aircraft generates an N-wave sonic boom signature (Figure 2) with a sharp rise in pressure followed by a rapid drop. This is audible on the ground as an impulsive sound, of very low frequency and short duration. The rapid onset can lead to startle and the low frequency content can also cause vibration and rattle indoors.

[28] “HISAC Environmentally friendly high-speed aircraft”, FP6-AEROSPACE, European Commission.

[29] H. Welge et all, “N+2 Supersonic Concept Development and Systems Integration”, NASA/CR-2010-216842, NASA, 2010.

Figure 2: Sonic boom generation, propagation and signature evolution[30]



Design improvements to the shape of an aircraft cross-section can alter the N-wave signature to reduce the peak and soften the sound of the boom to an acceptable level. This will potentially enable supersonic flight over land. A level of acceptability of sonic booms has yet to be determined and may only be established by flying a demonstrator aircraft having a low-amplitude shaped signature over communities[31].

Noise Modelling and Measurements

Modelling of supersonic aircraft has been undertaken for a long time and there is several software in place being used for calculations such as NASA's High-Speed Research Noise Prediction Code (HSRNOISE)[32], Japanese JAXA's Aircraft Noise estimation tool (AINEST)[33] and the Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design (SUAVE)[34].
These models have a much higher fidelity that models used for airport noise calculations, since they are intended to help optimise the design. Modelling is continuously being used

30 Taken from Plotkin KJ, "Review of Sonic Boom Theory", AIAA Paper 89-1105, 12th AIAA Aeroacoustics Conference, 10-12 April 1989, San Antonio, Texas.

31 J.Morgensten et all, "Advanced Concept Studies for Supersonic Commercial Transports Entering Service in the 2018 to 2020 Period Phase I Final Report", NASA/CR—2013-217820, NASA, 2013.

32 J. W. Rawls & J. C. Yeager, "High Speed Research Noise Prediction Code (HSRNOISE) User's and Theoretical Manual", NASA/CR-2004-213014, NASA, 2004.

33 J. Akatsuka, "Development of Aircraft Noise Estimation Tool (AiNEST)", ISSN 1349-1113, JAXA-RR-16-005, JAXA, 2017.

34 T. Lukaczyk et all, "SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design", Stanford University and Embraer.

to optimise design shape for the aircraft and engine components, improve numerical fidelity of the models and for comparison with experimental results. There are currently no recognised supersonic aircraft noise models for airport noise calculations recommended internationally or in Europe. This gap is expected to be addressed through planned ECAC and ICAO work programmes.

Experimental results are continuously being undertaken to validate noise modelling sources, measure the results from flight demonstration and flight capability projects.

Noise exposure and annoyance

For the current state of supersonic aircraft design, the noise exposure from supersonic flights are higher at landing and take-off and cause sonic boom during cruise flight, which cause disturbance if flight is over land.

Mitigations for landing and take-off noise exposure include reduction of noise at source (covered in the previous section) and operational measures. Supersonic aircraft may require special operational departure and arrival flight procedures due to their high speed and high thrust characteristics. Operational procedures would reduce the noise and emissions from supersonics, but this will still be an increase in noise and emissions compared to just subsonic operations. Similarly, operational procedures may have trade-offs between noise and emissions. Procedures currently used for noise modelling may require adaptation of the ECAC Doc 29[35] calculation methodology and ICAO ANP database format to appropriately reflect the new characteristics in the recommended aircraft noise calculation methods used in Europe and internationally.

NASA has recently conducted a city-wide quiet sonic boom test in the US, where 500 residents were recruited to provide attitudinal responses to the sonic booms they heard.[36] The test generated up to 8 booms per day for two weeks and was a trial of future tests planned with NASA's forthcoming X-59 low boom demonstrator aircraft, which is due for first flight in 2022 and community low-boom noise tests in 2023.[37] These tests are intended to help inform acceptable sonic boom limits.

The European Community has launched in 2018 a collaborative project called RUMBLE[38] (RegUlation and norM for low sonic Boom LEvels) that is producing the scientific evidence to determine the acceptable level of overland sonic booms and to come up with the appropriate ways to comply with these levels. It aims to produce the quantified evidence

[35] "Report on Standard Method of Computing Noise Contours around Civil Airports", ECAC Doc 29 - 4th Edition, 7 December 2016

[36] https://www.nasa.gov/aero/nasa-prepares-to-go-public-with-quiet-supersonic-tech

[37] NASA X-59 QueSST

[38] https://rumble-project.eu

needed to support new regulations for national, European and international regulation authorities.

Qualitative analysis

Range of potential noise impacts identified

Currently, the goal of potential manufacturers of supersonic civil aircraft is to target passengers that fly first class or business jets, forecasted to have 350 movements per day in UK in 2035[39]. Based on this level of uptake, the introduction of supersonics would impact on the noise exposure of airports and therefore have an impact on the Aviation Strategy: Noise Forecast and Analyses[40], developed based on subsonic aircrafts. Therefore, design improvements, different landing and take-off procedures, alternative routes and alternative airports may need to be utilised to accommodate these numbers of supersonic flights.

Currently, a supersonic aircraft will generate more noise exposure than a subsonic one on take-off and landing if it has to comply to subsonic ICAO design approval tests for landing and take-off. There is, however, uncertainty around how large the differences might be and to what extent future technologies and take-off and landing procedures might be adapted to reduce noise. For example, supersonic aircraft generate high drag at low speed and are therefore more amenable to a steeper approach procedure. Another way of mitigating the higher noise exposure from supersonic aircraft could be to use airports where less population is impacted.

During cruise, supersonic aircraft will generate sonic boom that, depending on the levels, may prevent supersonic flights over land. Aircraft design improvements to attenuate sonic boom and use of clearly defined routes may allow for introduction of supersonic flights over land.

Next Steps

As supersonic aircraft designs begin to mature there is a need to better estimate their noise characteristics and understand the implications for overall airport noise. There is significant uncertainty regarding the projected future fleets and there could be significant inter-airport differences, with potential for business jet airports to have a greater concentration of supersonic aircraft operations.

39 D. Rutherford et all, “Noise and climate impacts of an unconstrained commercial supersonic network”, Working Paper 2019-02, The international Council on Clean Transportation, 2019.

40 “CAP 1731 Aviation Strategy: Noise Forecast and Analyses”, Civil Aviation Authority, 2018.

Other environmental impacts that may need further consideration

Given the higher drag generation and higher speed, supersonic flight requires more thrust leading to greater fuel burn. With the higher fuel usage, engine emissions would increase. Beyond this, some noise reduction technologies, such as higher bypass ratio engines, could have much stronger adverse trade-offs with other environmental factors such as fuel burn and carbon dioxide emissions. NOx emissions from aircraft are already a concern, and although supersonics may have lower NOx emissions per unit thrust, they will have higher thrust.

Supersonic civil aircraft are also expected to fly at higher altitudes than existing subsonic aircraft (higher than 40,000ft). This could lead to greater climate impacts from NO_x and particulate emissions at these altitudes, including the depletion of stratospheric ozone. An up to date assessment of these impacts is required.

Chapter 4
Unmanned Aircraft Systems

Background

Unmanned Aircraft (UA or commonly known as ‘drones’) are aircraft that are flown without a human pilot aboard as the ‘flying part’ of an overall Unmanned Aircraft System (UAS) that includes the control data link and the station/device that the aircraft is controlled from. They are used in several industries and applications (photography, film and TV, surveying, emergency services use, reconnaissance, monitoring of building works, communications), as well as recreationally, and the opportunities both for industries and public sectors[41] are fast growing. Significant work is being undertaken to agree on general requirements for UAS operations. The environmental impact from UAs varies according to their size, power source, style of operation and the location of operation. Public concern primarily includes privacy issues, environmental impacts, noise pollution and disruption of visual amenity. An overview of current regulation, noise sources and noise exposure from UAS is given below.

International

ICAO Annex 16 Environmental Protection Volume I: Aircraft Noise[42] specifies the requirements for aircraft noise for aircraft that are issued with a Certificate of Airworthiness and engaged in international operations and thus do not apply to many types of UAS. The noise requirements for current aircraft categories would technically apply to UAS with similar airframes and propulsion systems as normal aircraft. Aircraft engine emissions standards could also apply to UAS if similar products are used as per ICAO requirements. Additional noise and emissions standards may be required as new aircraft types are developed, according to their classification under ICAO requirements[43].

[41] Taking Flight: The Future of Drones in the UK, Department for Transport, 2018.

[42] “Environmental Protection”, ICAO Annex 16 to the Convention on International Civil Aviation, Vol.1 Aircraft Noise, 2017.

[43] ICAO RPAS Manual Doc 10019.

Europe

The EC and EASA are developing new regulations for UAS[44], the work being undertaken under the EASA Rule making Task No 0230[45], where UAS operations are separated into different risk-based categories:

- Open Category: for small UAS with a maximum take-off mass (MTOM) of less than 25kg, flown within visual line of sight (VLOS) and to a maximum height of 400ft (120m). Flight within this category is based on a set of operational rules and no prior authorisation is required from the competent authority. The open category is further divided into three subcategories, A1, A2 and A3, which essentially cover flight 'over', 'close to' and 'away from' people.
- Specific Category: for operations that require an authorisation from the competent authority (i.e. the national CAA), based on a safety risk assessment. Essentially, this covers any operation that is outside of any of the limits of the open category. These operations could, with the appropriate authorisation, take place within congested areas and/or close to members of the public not involved in the activity. Operations could be conducted at any height.
- Certified Category: This category utilises the traditional method of regulating manned aviation when the aviation risks increase to an equivalent level. Operator certification, flight crew licensing and UA certification will be required due to the higher associated risk.

For UA that are to be 'placed on the market' (i.e. sold) for use within the open category, a new Delegated Regulation is being developed which places these UA into five subclasses (C0 to C4). Maximum sound levels have been proposed for Classes C1 and C2 (a mass of 250g to 900g and 900g to 4kg respectively). Although there is some uncertainty about the final maximum sound levels at present, the limits for classes C1 and C2 will make it unlikely that the operation of such drones would lead to adverse noise impacts. However, there are currently no proposed noise limits for larger drones up to 25kg in class C3.

For the open category, manufacturers will be expected to declare they meet these standards as part of the product standards that are also part of this regulation. Above 25 kg, the expectation is that UAs will follow standards like the ICAO standards for manned vehicles.

[44] Introduction of a regulatory framework for the operation of unmanned aircraft systems in the 'open' and 'specific' categories, Opinion No 01/2018, EASA, 2018.

[45] EASA Rule making Task No 0230

United Kingdom

The safety regulations related to UAs in UK are mainly contained in Articles 94 and 95 of the Air Navigation Order (ANO 2016)[46] which is referenced in CAP 393[47]. These are safety regulations and do not encompass matters relating to privacy and security. The ANO articles set limits on where drones may fly and whether they can be used for commercial purposes (commercial operations). There are currently no noise specific requirements for UASs in UK. The intent is that UK follows EC regulation.

Technologies used in UAS designs

The main categorization for UAS is currently determined according to their mass within the UK, within the UK, with 'small unmanned aircraft' being the term used for aircraft of 20kg or less. The proposed EU UAS regulations move to a risk-based categorisation (Open, Specific and Certified) as outlined earlier in the 'Europe' section.

UASs can also be described by type of wings, landing requirements, vertical/horizontal take-off and landing, number of rotors, fuel type, cargo/no cargo, manned/not manned. These are further explained in the paragraphs below.

In relation to wings, like all other aircraft, UASs can be either have fixed wing or rotary wings or use some other form of lifting device such as an airship/balloon.

In relation to landing requirements, they may need permanent requirements (controlled by planning permission), temporary (subject to control like helicopter use), prolonged temporary usage (like building sites) or no specific requirements (e.g. most blue light services and small UAS).

Horizontal and vertical landing can also differentiate UASs as they will require different power ratios for take-off and landing. Vertical take-off and landing requires a power-to-weight ratio greater than for conventional fixed wing civil aircraft.

Overall, the heavier the UA is, for the same configuration, it will require more thrust and power and is therefore likely to result in more noise, and therefore potentially a greater need for noise reduction technologies.

Although most UAs are battery powered, they can operate with other engines and fuel types.

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[46] ANO 2016, UK Statutory Instrument, 2016 NO.765

[47] "CAP 393 The Air Navigation Order 2016 and Regulations", CAA, September 2018.

Noise sources, modelling and measurement

Noise at Source

The noise from UAs are mainly due to: propeller(s), power source (electric motors or engine) and the interaction between them (airflow from propellers over the airframe, motors / engines causing vibration in the airframe, etc.).

For a given UA size, the higher the weight the more thrust and power will be required and will therefore result in more noise, and hence a greater need for noise reduction technologies. Spatial configuration plays a role on the specific noise characteristics and noise level will vary for different configurations. The electric motor tends to have a high frequency noise and contributes to the overall noise of an electric aircraft[48]. Other airframe interaction generates further aerodynamic noise.

Several actions can be undertaken, which may reduce the noise in some UAs: reduce weight of the aircraft and individual components; design larger and slower propellers; redesigning propeller blades, use passive noise reduction such as acoustic liners and active noise control to reduce tonal noise.

Noise exposure and annoyance

Adequate values for noise exposure from drones will be key for community acceptance. Currently UAs are not allowed to fly within 50 meters of any uninvolved person and 150m of any congested areas, which will limit some of the noise exposure. UAs can be flown close to 'people that are under control of the person in charge of the aircraft', provided they are not in danger. In addition, permission can be given to fly closer than 50m to uninvolved persons if the operator can provide an acceptable safety case. The safety case currently does not give any consideration to noise. Noise exposure will depend on fleet characteristics, volume of UA operations and the distance between the drone and exposed residents. For larger drones currently there are no maximum noise limits proposed. Noise management will be dependent on information on their noise emission, distance from population sources, number of operations and mapping of drone noise using metrics such as L_{Aeq16h} used for noise exposure contours. However, given the likely tonal noise content this may not reflect the level of annoyance, so other metrics may need to be considered.

From a noise modelling perspective, several institutions are developing modelling capability to estimate the noise from a UA sources, however they have not yet been validated for UK and international use. European Civil Aviation Conference (ECAC) is considering using the same modelling tool[49] that has been developed for helicopter noise

48 B. Henderson, "Electric Motor Noise from Small Quadcopters: Part II – Source Characteristics", AIAA/CEAS Aeroacoustics Conference, 2018.

49 https://www.easa.europa.eu/easa-and-you/environment/impact-assessment-tools

developed by EASA and the European Commission, using source hemispheres and spherical noise source propagation.

The level of annoyance due to UA's noise exposure will require further research to understand the relationship between source noise, operations and public acceptability.

Whilst the development of noise modelling of UAs and initial field measurements is beginning, current users are exploring which levels may be acceptable. For instance, Uber[50] has set a goal not to increase the long-term average Day Night Level (DNL) by more than 1 dB.

Qualitative analysis

Range of potential noise impacts identified

Market forecasts[51] estimate that the number of UAs in UK by 2030 will be around 76,000.

In UK changes to UAs of class C1 and C2 will happen shortly, following from Government legislation[52], to be 50 meters from any person, 150m from any congested areas and 5 km from aerodromes. Class C3 and C4 are not to be used near population unless authorisation is granted.

Given that for class C1 UA the maximum sound power level will be at most 85 dB(A), it is not expected that these drones in isolation would have a large noise impact during day time. However, during night time and in remote areas these levels of noise could cause annoyance depending on number of operations.

Depending on activity undertaken by UAs they are entitled to enter the airport areas and therefore the noise impact would depend on the volume of flights in the area.

For UAs prevented from flying closer than 5 km from airports without permission, they are unlikely to make a difference to the airport noise levels. However, if preferential routes are established for drones and they are operated at height of 400 feet (120m) above residential populations, the noise levels from UAs could exceed the ambient noise levels close to established UA routes.

50 https://www.uber.com/elevate.pdf

51 "Skies without limits: Drones – taking the UK's economy to new heights", 180515-162604-JM-OS, PWC

52 http://www.legislation.gov.uk/uksi/2019/261/made

Interim approach

From a noise modelling perspective, making progress towards having a noise modelling tool to address both helicopter and drones is essential for future quantitative assessments. The use of the same modelling tool that has been developed for helicopter noise developed by EASA and European Commission, using source hemispheres and spherical noise source propagation would allow for speed of implementation and shared measurement costs.

There is also a need to better understand if preferential routes are being established for drones, such that quantitative assessments can be undertaken to better understand the noise exposure that it may cause.

Other environmental impacts that may need further consideration

Other environmental impacts from drones will depend on the fuel mix utilised by the fleets. If fuels are used, air quality and GHG emissions associated with their use should be analysed.

Chapter 5

Spacecraft

Background

The Government's Industrial Strategy[53] sets out its vision for the UK space sector and its aspiration to facilitate commercial spaceflight launches from the UK, providing opportunity for low cost access to space and to strengthen the UK economy. The UK's Spaceflight Programme[54] aims to grow the space economy by facilitating the development of a sustainable business market for the sector. This is being done by creating market incentives; by introducing the Space Industry Act 2018[55], which allows for the development of a modern regulatory framework; and by strengthening international engagement. With the introduction of this programme, there is a need to understand its environmental impacts, including noise from spacecraft and spaceports as well as any noise impact that this programme may have in relation to the Aviation Strategy.

International

There are currently no international agreed standards for spaceflight and no international body with oversight responsibility for it.

Europe

At present the EU space sector is governed by five EU regulations[56], however the EU Commission is putting together a new regulation[57] that aims to simplify and streamline the existing ones by combining them together. The main goals of the EU's new space programme are to ensure leadership, foster innovative industries, create autonomous access to space, and simplifying governance. The EU Space Programme[58] for the 2021-2027 period will focus on EU's global and regional satellite navigation systems, earth

53 "Industrial Strategy, Building a Britain Fit for the Future", HM Government, November 2017, ISBN 9781528601313

54 "UK's Spacecraft Programme", HM Government, July 2018.

55 "Space Industry Act", HM Government, 2018.

56 Regulations (EU) No 1285/2013, (EU) No 377/2014, No 541/2014/EU, (EU) No 912/2010, and No 1104/2011/EU.

57 "Space strategy for Europe", European Parliament resolution, September 2017, 2016/2325(INI).

58 "EU Space Programme", EU Legislation in Progress 2021-2027 MFF

observation programme and security programme. Defra will transpose this from EU to UK law in due course.

UK

As part of the UK Government's Industrial Strategy[59], the Government will invest around £8bn per annum by 2020 in research and innovation across the UK, including space and future satellite technologies with the aim to create low cost access to space and realise its commercial opportunities. The Government's intention is to work with industry to grow UK's share of the global space market from 6.5 per cent to 10 per cent by 2030.

To support this strategy the Government has put in place a Space Industry Act 2018[60] that allows for the development of a modern regulatory framework needed to ensure spaceflight from UK spaceports is safe and managed responsibly. The Government has also allocated £50m for the Space Flight Programme[61] to enable new satellite launch services and low gravity spaceflights from UK spaceports.

Several sites in England, Wales and Scotland have come forward to have a spaceport with plans that could enable access to a global market for launching small satellites. The decision for a site to acquire a licence will require an environmental impact assessment, where applicant sites will have to assess the noise, ground-borne vibration, air-borne vibration and sonic boom effects caused by the spacecraft launches.

[59] "Industrial Strategy – Building a Britain fit for the Future", HM Government, November 2017.

[60] "Space Industry Act 2018", HM Government, 2018.

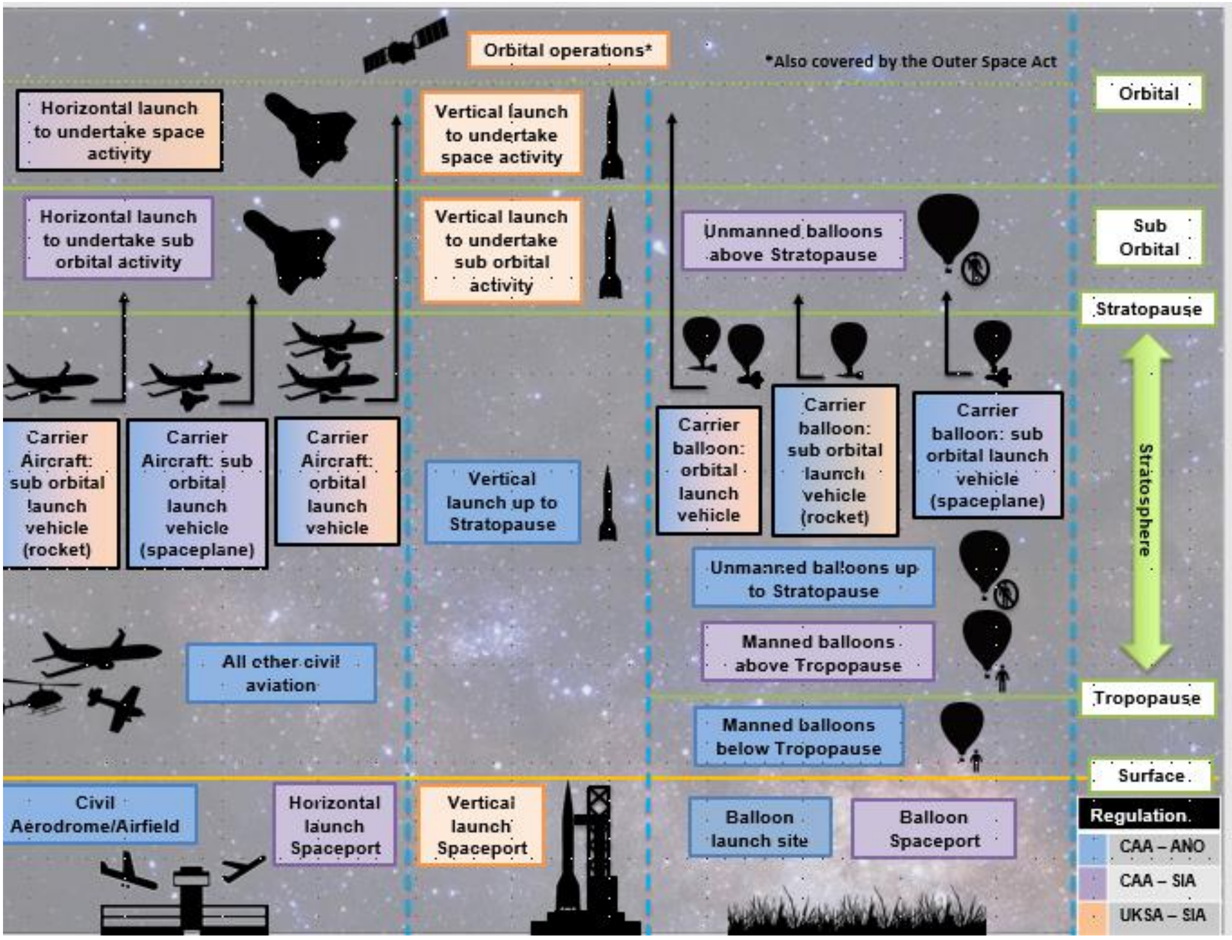
[61] "Launch UK – Access to space from UK spaceports", UK Space Agency, Department for Transport and Civil Aviation Authority, July 2018.

Technology designs

Vehicle configurations

The two main types of vehicle configurations are vertical launch rocket and spaceplanes, the latter of which fly either in isolation or with a carrier aircraft (carrying a rocket or a spaceplane), as presented in Figure 3 according to their operation type (orbital and suborbital and stratosphere) and take-off mode (vertical and horizontal).

Figure 3: Types of spacecraft and their operations[62]



Rocket spacecraft are spacecraft that derive thrust from using a rocket engine and space planes are winged vehicles that act as an aircraft while in the atmosphere and a spacecraft while in space. Table 2 presents an overview of the types of spacecraft, operations, take off launch utilised and main power sources.

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62 Commercial Spaceflight Regulation Team, CAA, 2018

Table 2: Characteristics of main types of spacecrafts

Type of spacecraft	Operation	Take-off	Power sources
Rocket	Orbital	Vertical	Rocket engine
Rocket	Sub-orbital	Vertical	Rocket engine
Carrier aircraft / rocket	Sub-orbital	Horizontal	Carried by carrier aircraft followed by rocket engine
Carrier aircraft / space plane	Sub-orbital	Horizontal	Carried by carrier aircraft followed by rocket engine
Carrier aircraft / space plane or rocket	Orbital	Horizontal	Gas Turbine / Rocket engine
Space plane	Sub-orbital/Orbital	Horizontal	Jet powered take off followed by rocket engine; or rocket powered take off and flight

Noise sources, modelling and measurement

Noise at Source

The noise sources from spacecrafts will vary according to the space craft type as presented in Table 2.

For rockets, with vertical take-offs, the first few minutes noise is dominated by "lift-off" noise is caused by the engine firing and initial lift-off. After these initial stages, the main noise source in vertical rockets is the jet noise associated with rocket engine and will vary with exhaust velocity and nozzle exit diameter. Horizontal drift that happens at vertical take-offs can significantly increase the noise levels[63]. Other sources of noise at lift-off come from vibrational response noise from a supersonic jet impinging into other parts of

[63] C. Lubert, "Sixty years of launch vehicle acoustics", 174th Meeting of the Acoustical Society of America, 2017.

the rocket[64],[65],[66]. Depending on fuel used, there may be combustion in the exhaust flow that can cause additional noise[67].

The noise power spectrum has broadband characteristics and is proportional to the exit velocity to the power of 3 (V^3)[68]. Noise is radiated in all directions; however, the magnitude of the acoustics field is highly directional[69].

For horizontal take-off spaceplanes, the noise sources are related to combustion, exhaust plume noise and flight parameters. All these types would reach supersonic speeds during launch and generate sonic boom during launch. For spaceplanes, powered by jet and rocket, the noise is initially jet noise followed by rocket noise (combustion and exhaust plume noise), whereas for spaceplanes power by rocket, the noise will be dominated by rocket noise. For spacecraft using a carrier aircraft, the noise is initially dominated by turbofan engine jet noise associated with the carrier aircraft, followed by rocket noise. As the spacecraft goes up, the distance to the ground increases and the air becomes less dense, reducing the noise exposure on the ground. On landing, the spacecraft that are not powered, won't generate any noise, however they will generate a sonic boom on re-entry. However, powered spacecraft will generate noise.

Noise Propagation

Most noise propagation modelling for spacecraft, regardless of spacecraft type, assumes a point source that radiates with a spherical field[70] although others use cylindrical propagation for the initial launch stages[71]. Ground interference, atmospheric turbulence and atmospheric absorption need to be taken into consideration as well as non-linear impacts due to the high amplitude of the noise source with presence of shock waves. As the vehicle ascends, the separation distance increases and the air become thinner and therefore reducing noise transmission. On the other hand, if vehicles descend at

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64 "Summary of Supersonic Jet and Rocket Noise", 174th Meeting on the acoustical Society of America, 2017.

65 "Identification of Noise Sources during rocket engine test firings and a rocket launch using a microphone phased-array.", J. Panda, NASA Langley Research Centre, 2013.

66 M. James, "Full-scale rocket motor acoustic tests and comparisons with empirical source models", 164th Meeting of the Acoustical Society of America, 2012.

67 NASA, "Prediction of Acoustic Environments from Horizontal Rocket Firings, AIAA Aeroacoustics Conference, 2014.

68 J. Haynes, "Modifications to the NASA SP-8072 Distributed Source Method II for Ares I Lift-off Environment Predictions", NASA_SP-8072, 2009.

69 James M. et. al, "Modification of Directivity Curves", AIAA, 2009.

70 M. Morshed, "Prediction of Acoustic Loads on a Launch Vehicle: Nonunique Source Allocation Method", Journal of Spacecraft and Rockets, Vol. 52, No. 5 (2015), pp. 1478-1485.

71 M.Muhlestein et all, "Prediction of nonlinear propagation of noise from a solid rocket motor", 2013 Rocky Mountain Space Grant Consortium, 2013

supersonic speeds, the transmission from high shock waves will be higher at lower altitudes.

Noise Modelling and Measurements

Noise Modelling

The modelling of noise sources continues being improved and software for spacecraft noise prediction are being used[72], showing steps to calculate rocket noise. Other examples include RUMBLE[73], a high-fidelity launch vehicle simulation model that has been developed to predict community noise exposure from spaceport launch, re-entry, and static rocket operations. There is an emerging need for rocket environmental noise modelling and impact criteria given that aircraft noise and rocket noise may require different impact criteria[74].

Noise measurements

Several pieces of work are being undertaken on improving spacecraft noise measurements to improve noise source identification and intensity patterns as well as for validating initial noise assessments and for measuring noise impacts. Further measurements and research are needed to improve rocket source characterization, long range sound propagation and environmental and community impacts from different rockets. Given the variation on spacecraft types, spaceport types and frequency of launches a noise certification approach for spacecraft may not be of value.

Noise exposure and annoyance

In the US, there are two aspects commonly addressed when dealing with spacecraft noise exposure. The first aspect is hearing conservation, where the population exposed to high levels of noise based on an A-weighted maximum level (115dBA) is identified from noise contours and local population data to flag areas of concern. The second aspect is the identification of the probability of structural damage property, where maximum noise levels and housing data are used to estimate risk of property damage.

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72 "Rocket Noise Prediction Program", R. Margasahayam et all, NASA.

73 "Summary of Supersonic Jet and Rocket Noise", 174th Meeting on the acoustical Society of America, 2017.

74 C. Choi, "Space Forecast Predicts Satellite Production Boom", Space.com, 2009 https://www.space.com/6839-space-forecast-predicts-satellite-production-boom.html

Noise impact

Noise from spacecraft can pose challenges to community relations near airfields. Accurately predicting and quantifying community impacts is important to minimize such impacts and reduce annoyance. Calculated metrics can be used as inputs for a model of perceived annoyance used to estimate the relative contributions of loudness and other sound quality features to annoyance. Currently Day-Night Average Sound Level (DNL) is required by FAA to identify community annoyance[75]. Although this metric is widely used, it may not be the most applicable for rocket launches. At an airport, the number of aviation movements is high and they occur on a more or less continuous basis, which supports the use of day and night average noise metrics. However, it is recognised that at a spaceport the number of launches will be limited compared to normal aviation movements and it is likely that noise will be subject to a window of a few minutes rather than the all-day experience currently felt by those living at airports.

Qualitative analysis

Range of potential noise impacts identified

It is difficult to estimate the numbers of vertical launches per year, but it will be very low for the first few years. Individual launch operators have indicated a long-term aspiration for 6-12 launches per year, but none of that is firm. Therefore, the noise impacts should be based on event duration and rather than day or other long-term averages.

Next Steps

As part of the Secondary Legislation associated with the Space Industry Act, DfT will publish guidance to enable the development of the UK space industry; this is hoped to be in place by the early 2020s. This will include the requirement for an Assessment of Environmental Effects (AEE) to have been completed prior to the granting of a spaceport licence or a launch operator licence authorising launches of spacecraft and/or carrier aircraft. The development of the AEE is being widely consulted across UK environmental bodies to ensure a consistent approach.

[75] "Final Programmatic Environmental Impact Assessment for Horizontal Launch and Reentry of Reentry

APPENDIX I

Noise Sources

A general introduction to noise generated by flow is given in this Appendix. This will facilitate the explanation of noise arising from each specific type of new technology. This covers noise from fan, turbine, combustion, jet, supersonic flow, airframe and electric motors.

Fan Noise

Overall the fan noise will be characterised by broadband and pure tone noise. Noise prediction methods employed for fan noise generally follow the approach presented by Heidmann[76]. The noise from fans and compressors will be in general be more relevant for noise exposure during aircraft approach to airports.

Turbine noise

In exhaust systems of gas turbine engines, the turbine flows normally generate significant tonal components superimposed on broadband noise[77,78].

Combustion noise

The combustion noise is characterised by its broadband spectrum and directional distribution. However, due to the resonance of the combustor, the radiated noise has sharp peaks, superimposed on the broadband noise[79,80].

Jet Noise

A jet spectrum is characterised by its broadband characteristics and by certain tonal components. The acoustic power and spectrum of a jet is generally proportional to the jet exhaust flow velocity to the eighth power[81,82].

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76 Heidmann, M. F., “Interim Prediction Method for Fan and Compressor noise source, NASA, TM-X-71763, NASA, 1975.

77 Sears, W.R., Some aspects of non-stationary airfoil theory and its practical application. Journal of Aeronautic Sciences, 1941. 8(3): p. 104-108.

78 Goldstein, M.E., Aeroacoustics. 1976: McGraw-Hill International Book Company.

79 Crightol1, D.G .D. , Dowling, A.P., Ffowcs Williams, .I .E., Heckl, M., Leppington, F. G., Modern Methods in Analytical Acoustics. 1996: Springer-Verlag.

80 Smith, M.J.T., Aircraft Noise. 1989: Cambridge University Press.

81 Lighthill, M.1., On the sound generated aerodynamically f. Proc.Roy.Soc .A, 195 1. 221: p. 564-587.

82 Lighthill, M.1., On the sound generated aerodynamically If. Proc.Roy.Soc.A, 195 1. 222: p. 1-32.

Supersonic Noise

Supersonic speed occurs when an aircraft's speed is greater than the speed of sound. When the aircraft moves faster than the noise waves it is producing, no waves will form in front of the source but will pile up behind and become compressed. The waves are then confined to a cone creating high-pressure regions outside the compressed waves. This border from inside to outside is the shock wave. The aircraft will generate at least two shock waves, one related to the front of the aircraft and one related to the back. These shock waves create a very low frequency sound (boom), with the noise event lasting less than one second and peaks after around one tenth of a second. Given the lack of warning of the noise event, there is a risk of startle as well as disturbance.

It is now understood that through careful shaping of an aircraft shape, the noise signature can be altered to soften the sound of the boom to an acceptable level, potentially enabling supersonic flight over land.

An overview of models used for estimating sonic boom is presented by Maglieri[83].

Airframe Noise

Airframe noise includes broadband noise from the fuselage, wing and landing gear. The method for airframe noise prediction developed by Fink[84] is widely used for airframe noise.

83 D.Maglieri et all, "Sonic Boom – Six decades of research" NASA/SP-2014-622, NASA Langley Research Centre, 2014.

84 Fink, M. R., "Airframe Noise Prediction Method," Federal Aviation Administration Rept. FAA-RD-77-29, Washington, D.C., 1977