

The noise reduction techniques for Unmanned Air Vehicles

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Abstract— Most of the unmanned air vehicles (UAV) were developed with military purposes and freely used without any regulatory concerns. UAVs are expected to be used at the commercial applications in near future. The noise generation mechanism of conventional aircrafts, reduction techniques and regulatory goals are outlined in the paper. Similarly, the noise generation and control for the UAVs are discussed. Study, indicated that future studies are needed to control the noise of UAVs better and regulatory involvement is essential to keep their impact minimum on human health and environment.

I. INTRODUCTION

Unmanned air vehicles (UAV) have been used for many tasks including surveillance, reconnaissance, target acquisition, relaying communications, delivering small items, working as decoy and many others. Any size UAV including the nano, micro, mini through large UAVs should be well designed and properly configured to perform the assigned tasks. The structure, aerodynamic profile, electro-mechanical components, sensors, power source, computers, propulsion system and other components have been selected by considering mainly the required payload, operational distance, altitude and speed. The aero-acoustics of the UAVs has been gaining importance with the maturity of the available UAVs. To give them system stealth feature or not to disturb people while operating at the populated areas, the aero-acoustic of the propulsion system should be carefully studied.

The length, wingspan, payload, weight, endurance, cruise speed are carefully selected during the design stage of the UAVs [1]. Most of the existing propulsion systems of UAVs were initially designed by considering the basic operation conditions including the dimensions, weight, flight distance, altitude, atmospheric conditions and operation time. They may use electrical motor(s), internal combustion engine(s) (piston engine, Wankel), turbines such as Turboprop, turbojet, turbofan, propfan), rocket(s), Pulse/Scram/Motor/Ram –jets. Fuel cell(s) or solar panels may be used to generate the electricity during the operation of the system.

The electrically powered UAVs are usually powered by (a) batteries (good for small size aircrafts due to the weight versus energy density), (b) fuel cells (good for high altitude UAVs due to their high effective energy density), (c) Solar cells (good for very light aircrafts, for long endurance flies, with simple missions in calm and sunny weather conditions).

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The advantageous of electrical Unmanned Air Vehicles (UAVs) over fuel burning combustion engines are the following: (a) less noise, (b) lower heat signature, and (c) capability of handling higher altitude cruises (jet engines may not perform well at low air pressures).

Various types of fuel-cells are available for UAVs: Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell – PEMFC, Alkaline Fuel Cell – AFC, Phosphoric Acid Fuel Cell – PAFC, Molten Carbonate Fuel Cell – MCFC, and Solid Oxide Fuel Cell – SOFC [2] [3]. One important advantage of fuel-cell powered UAVs (i.e. hydrogen-powered) over the battery powered ones is the decreasing weight with flight when the fuel is consumed. The weight of the battery doesn't decrease when the energy is consumed. Similarly the fuel weight of fossil burning propulsion systems decreases with consumption. The efficiency of fuel cells is quite high (i.e. 55% at 40-200 Watt at steady state) [4]. Recently, fuel cell based propulsion systems gained popularity for small UAVs and their characteristics were well studied [4].

II. WHAT IS NOISE

A. Human perception aspect

Noise is the human perception of unwanted sound. Human sound perception is constrained in a window where the sound intensity and frequency draw the boundaries [5]. This window is called *equal-loudness contour* where the frequency range is between 20 Hz and 20 kHz and loudness level is between 0 dB (20 micro Pascal) and 140 dB (immediate deafness). The recently determined equal-loudness-level contours are referred as Fletcher-Munson curves and available as ISO 226:2003 [6].

Noise is a perceivable sound wave or a combination of waves that can be described with three acoustic properties: (a) *loudness* as a physical strength, it ranges from quiet to unbearably disturbing levels depending on the amplitude of the wave, (b) *frequency* is the vibration rate ranges from low to high pitch, and (c) *phase* is the shift between the waves. A change in sound level of 3 dB is *just-noticeable*; an increase/decrease of 5 dB is *surely-noticeable*; and a variation of 10 dB up/down is perceived as doubling or halving sound level [7].

In addition to the noise assessment that use a simple tone sound; recently complex sounds are classified in three categories based on their source [8]. These categories are the following: (a) *Anthrophony* (human-produced), (b) *Geophony* (geophysical) and (c) *Biophony* (wild animal).

The sound perception of humans is far more superior compare to the vision perception. Brain's response time to sound is much faster (10~30 ms) than the vision [9][10]. The sound conveys the information from a sound-source, source characteristic, as well as the surroundings. Similarly, one dimensional digitized sound signals can be analyzed faster and more reliably compare to the 2-D data of vision systems by the computers.

B. Noise pollution: effects on human health

The excessive noise has harmful effects on human health [11]. The psychological and physical effects of aviation related noise on the community (i.e. schools children) have been studied [12]. Some of the noise related human health problems listed in the recent studies are the following: permanent hearing loss [13] when located near to jet-engine), sleep disorders [14], mental problems [15] and cognitive issues [16], learning disabilities [17, 18], cardiovascular problems [19] and hypertension [20]. Reduction of the exposure to noise have been suggested to minimize the harmful effects of environmental noise of the aviation industry [21] and World Health Organization has been addressing the community noise problems [22] since 1980s.

C. Types of Noise and compliances of standards

The classification of noise is defined by the International Standard Organization (ISO). The noises emitted by machinery and equipment are classified as steady, non-steady, fluctuating, tonal, isolated bursts of sound energy, etc., according to ISO 12001 [23]. ISO 362-1:2007 deals with the sounds of accelerating road vehicles. The aircraft noise measurement and reduction techniques are discussed in International Electrotechnical Commission - Technical Committee (IEC-TC) 29. 61265 is a standard for the measurement of transport-category airplanes by using one-third-octave-band sound pressure levels for noise certification. The International Civil Aviation Organization (ICAO) certificate the airplanes based on "Doc 9501" of ICAO. ICAO deals with the noise levels during the landing and take-off stages of the flight. ICAO suggests several methods for the management of aircraft noise by considering the engine, aircraft type, power, flaps and external sources like weather condition [24]. The noise level of jet engines is usually around 100 and 105 dB during the takeoff or landing [25]. The measurement of noise is also categorized for a specific family of machinery and equipment by ISO 12001 ("Noise emitted by machinery and equipment - Rules for the drafting and presentation of a noise test code"). Several fields can be defined for testing purposes: *Free, Far, Reverberant, Direct, and Near-fields*.

D. The importance of Noise reduction program: government initiations

Similar to ICAO's studies, Federal Aviation Administration (FAA) issued the "*Order 5050.4 and Directive 1050.1*" for Environmental Analysis of Aircraft

Noise near Airports for land assessment. Federal Aviation Regulations Part 150 introduces the Airport Noise Compatibility planning program to recommend an acceptable noise level in the neighborhoods of the airports. Environmental Protection Agency (EPA) additionally published the Noise Assessment Guidelines (EPA 550/9-74-004) in 1974 for "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," [26].

Europe Clean Sky Integrated Technology Demonstrators, Europe Single European Sky ATM Research and US FAA "*The Next Generation Air Transportation System*" program all expects (a) less noisy, (b) more fuel efficient and (c) more environmentally friendly "*green*" aircraft technology. Substantial funding is available for encouragement to reach to these "ambitious" targets in several stages by 2017, 2020 and 2025, [27].

E. Sources of Aircraft Noise

Decreasing airfare costs, convenience, increasing competition helped the growth of airlines and air transportation companies. The number of planes in service have been steadily increasing and they pollute the environment with excessive noise and greenhouse gas emissions [28].

Within the current two decade period extending from 2010 to 2030, 700 million airline passengers are expected to be doubled. Four stage noise reduction policies will be implemented in this period. The noise reduction technology is expected to change the noise level as much as -32 dB by 2015, -42 dB by 2020 and -71 dB by 2025 for specific engine types (i.e. 737-800 with CFM56-7B) [29].

The noise of the aircraft is mainly created by two sources: (a) propulsion system (i.e. jet engine, turbo-machinery, combustor, and etc.) and (b) aerodynamic noise (airflow around the control and aircraft fuselage surfaces). Many researchers have worked on the reduction of aircraft noise created by the propulsion systems (Table 1) compare to the aerodynamic aspects due to the complexity of the issue. For each aircraft, the airflow patterns are different and additional noise may be created by external perturbations. In a recent study the effect of the aerodynamic of aircraft on the noise generation was studied. The importance of the characteristics of the leading edge of the aircraft wings was observed. The aero-acoustic study of the leading edge slat configuration showed that: (a) the slat angle and the created high frequency noise levels are proportional, (b) closing off the slat gap reduced the noise level by 14 dB, and (c) thickening the slat trailing edge reduced the vortex shedding. The slat noise components are usually related to the trailing edge noise caused either from the suction or the pressure at the surfaces of the slats [30]. A wind turbine study investigated the noise created by the trailing edge and airfoil. The noise of the wind turbine depended on the wind-direction and its characteristics showed resemblances to the observations of the aircraft noise reduction studies [31-33].

F. Using noise for tracking air-vehicles

The noise of the airplanes may be used to track their location and to identify them. A set of microphones of the *Acousto Seismic Air Detection system* could be used to monitor the sound of planes when they fly at the low altitudes (while they hide from the RADAR cone) [34]. The characteristics, including the type and model of the planes may be estimated from the digitized sound.

III. NOISE REDUCTION FOR AIRPLANES

In this section, noise reduction methods will be outlined in five sub-sections. First, conventional noise control methods by modifying the structure will be listed. Secondly, futuristic methods will be presented. Third, the reduction of engine noise will be discussed. Forth, the other operation time adjustment methodologies will be presented. In the last sub-section the noise reduction targets of the federal agencies will be outlined in the last sub-section.

A. Conventional noise control methods by modifying the structure

Mainly, two types of noise reduction methods are used for the aircrafts: (a) passive and (b) active techniques. The passive noise reduction techniques mostly modify the aircraft structure. They use various vibration-absorbing materials on the structure to reduce the noise in a limited frequency band. Dealing with the low frequency-noise (≤ 200 Hz) is more challenging than the high frequency noise [35]. The active noise reduction techniques use electromechanical systems. The following approaches are used with this purpose: (a) active-structural control, (b) active-isolation control, (c) active-noise control and (d) Hybrid control which combine these three systems. A closed-loop active noise control system may reduce some high frequency noise by a few decibels; where 3dB difference intensity is a just-noticeable sound reduction [36]. It is sometimes possible to reduce the noise by decreasing the vibration of surfaces. The active control systems may be utilized with this purpose. *Piezoceramic* actuator(s) may be attached to the skin of the aircraft. The 10-15 dB noise attenuation was reported when this approach was used [37].

B. Futuristic methods

The dimensions and shape of the aircraft's wing are selected according to the design objectives of the aircraft. Some compromises are needed during the design. Generally, designs which create low noise also have favorable drag coefficients or a lift load (C_L). However, they may not be suitable from the fuel consumption point of view and limit the fly endurance. The bio-mimics of the owl wing is proposed by using two types of materials with opposite properties (hard and soft elastic) to be used at the leading and trailing edges of the wings of airplanes. Future

aircraft wings may resemble the owl wings where rigid and soft formation of the down feathers reduce the noise while it flies for hunting [38]. Another characteristic of the owl wing which is called "V-ring" surface cylinder may help to reduce the aerodynamic noise further. That feature reduces the noise about 4.1 dB during the flight of owls [39].

Modification of the geometry of the aircraft wings or wind-turbine blades has recently been studied to improve the efficiency and reduce the noise at the same time. The geometry of leading and trailing edges of the blades were considered. The study confirmed that selection of a geometry creating the leading-edge tubercles is beneficial for the blades of wind turbines [40, 41] and aircrafts wings [42]. In terms of stealth capability, acoustic manipulation may be achieved by using *acoustic metamaterials* on acoustic field rotator [43]. Similarly, the efficiency of the fuselage can be improved by covering it a shark-skin type layer [44]. Special paint or similar coating may be used to reduce the drag and noise [45].

The tubercles created by the flapping wings at the leading-edge may improve aerodynamic characteristics during gliding flight [46]. This aerodynamic advantage affects the aero-acoustic of the aircraft and may indirectly help reduction of noise.

C. Reduction of engine noise

The noise of turboprop aircrafts that is mainly created by the propeller blade passage low frequency vibration was reduced up to 20 dB by using an active noise control system [47].

Several noise reduction techniques were developed for the jet engines of military aircraft. The nozzle structure of the jet engine is one of the main noise creators. Different nozzle designs have been evaluated to reduce the noise:

- (a) The geometry and configuration of the chevrons' nozzle exit or multi-phase flows in complex combustor/ augments geometry or the fan flow deflectors, [48, 49]
- (b) using steady fluidic or more effective flapping injection, [50]
- (c) addition of chevrons to the nozzle lip for significantly reduction of crackle noise that may be caused by a high-powered take-off and landing, [51]
- (d) using an active noise control system [36].

Another successful active control of sound system has already been tested for a confined space [52].

The noise of the propulsion system may be reduced 3.5 dB (A) with structural modification [53]. The Active Noise Control Fan has been tested with two circumferential arrays of acoustic actuators to reduce jet noise about 6 dB [25]. Active Noise Control can be used as an alternative to add-on noise reduction system for turbines [54].

The system dynamics of the propeller powered fixed-wing aircrafts (i.e. C130 Hercules) may be used to control the vibration and noise. The *synchrophaser* [55] slightly changes the phase between the propeller sets to control the plane vibrations. The noise of the plane could reduce up to 10 dB [56] when the structural vibrations are reduced.

The impacts of the components of the aircraft propulsion systems generate considerable noise. In last three decades, turbo engine noise reduction techniques have been developed to minimize the impact and sound levels were dropped below 100 dB by modifying blades and controlling the rotation speed [54].

D. Operation time adjustment based approach

The noise propagated from the aircraft and its perception relative to the other noise may vary with the time of the day. The noise dissemination in the morning hours would be much different than nighttime. The time of the day and fly path affects the aircraft noise. Relocation of the aircraft fly-path according to the time of the day is proposed at the highly populated areas [57].

E. Noise reduction targets of the federal agencies

NASA and FAA have been working together for a less noisy environment. Aircraft Noise reduction program was introduced in mid 1990s. The objective was to reduce the perceived noise levels by a factor of two (10 dB) till year 2007 and by a factor of four (20 dB) till year 2022. The noise levels are supposed to fall below 55dB (defined by the EPA) noise level at the last stage [58].

The flight-noise characteristics of rotary wing and jet engine powered fixed wing military aircrafts have been investigated for an environment impact study by the Department of Defense (DoD) noise program [59]. In the civil aviation sector, Canadian Aviation Environmental Working Group developed noise source reduction projects. These studies covered airframe, forced mixer and nozzle, as well as transonic fans. The Canadian Aviation Environment Technology Road Map targeted to reduce the noise under the Green Aviation Research and Development Network program [27].

If the noise of the aircraft cannot be prevented than the noisy areas should be defined and noise maps should be prepared to detect human health issues as soon as they develop. The noise maps of many airports in USA and Europe has been prepared. Similar map was also prepared for the Atatürk Airport in Istanbul [60].

IV. NOISE REDUCTION FOR UAVS

The noise of aircraft and UAVs in a free field create reverberation [61]. The acoustic properties of the environment effect the propagation of the sound and create reflection, scattering, spreading absorption and attenuation.

As a result, the acoustic properties of the noise will be different according to surrounding, weather conditions and even the vegetation.

The noise of the UAV's are mainly created with three sources. First, the propulsion system convert the energy of the fuel into the thrust. Secondly, the flow of the air around the fuselage create sound. Third is the vibration of the structure with the forces.

The noise of the propulsion system is significant during the typical flight of the UAVs. A Fuel cell "electrical" powered UAV operate more efficiently, and create less vibration and noise compare to a UAV which use combustion "gas" type propulsion system especially at the high altitude operations. Turbo charger of the combustion engines are generally used during the high altitude operations. The fuel cell systems drawback is their low power density compare to conventional fuels [62]. Extra back up batteries may be used to overcome this weakness [3]

Most of the UAVs operate at the lower speeds compare to the commercial and military aircraft. The noise generated by the airflow could be considered less significant at today's operating conditions.

The propulsion system of the UAV create structural vibrations. In addition, gust of wind, fluctuation of temperature at the different parts of the aircraft, high altitude radiation effects on composite materials create vibration. These vibrations generate noise. The ambient vibrations may be converted into electricity and power some sensors [63, 64]. The noise may be reduced by absorbing the structural vibrations. However, these vibrations may be used for better energy dissipation, [65].

A. What is the future UAVs' fuel system?

Hydrogen is the ideal fuel for the less noisy and more environment friendly UAVs. However, hydrogen gas production is very challenging because of the low efficiency of the process. The efficiency of solar-to-hydrogen conversion is typically around 1.7% [66-68] and most recent studies reached to 4.9% [69]. This hydrogen production method is more suitable for sunny locations with many sunny days. Alternative hydrogen production methods use a super bacterium [70], green algae [71] and waste materials [72].

The efficiency of the solar cell – battery combinations has constantly increased in last 30 years. For example, the efficiency of Li-Po battery with mono-crystalline solar panels reaches to 22.6% [73]. Such systems are very promising for small and light UAVs operating at very high altitudes.

B. UAVs' propulsion system

The propulsion systems of the UAVs can be classified according to their energy source. The propulsion systems of the typical UAVs obtain their energy from electrical (solar, hydrogen fuels) and chemical (see Table 1 for a comparison) energy sources.

Electrical propulsion systems may use (a) battery, (b) solar panels or (c) fuel cells with the aid of some batteries or (d) a hybrid system combining more than one of the listed power sources. The electrical systems of the sophisticated UAVs require complex active control systems to manage the system [74]. The performances of the hybrid electrical propulsion systems have been testing for small model aircrafts [75].

The high energy density of chemical energy sources makes the turboprop engines attractive. However, their fuel consumption, efficiency and noise require extensive studies to compensate their limitations in these aspects [76]. In order to increase the fuel efficiency of the aircrafts, the hybrid electric integrated combustion engine powered propulsion system has been studied to increase the fuel efficiency %15 [77].

Besides, the propulsion system induced noise, the propeller noise of electric powered engines was studied. The study indicated that the mean thickness of the blade, and the rotational frequency has to be carefully optimized to create minimum noise during the flight [78].

In summary, electrically powered propulsion systems are good choices compare to the others for UAVs. However, two important issues are the (a) power density of the energy source and (b) the required maximum power to mass ratio should be acceptable at the operating conditions of the UAV [79].

V. RESULTS AND DISCUSSION

The size and weight of UAVs are closely related to the operation altitude of the aircraft. High altitude aircrafts have usually larger wingspans and lower threshold speed (slightly below the stall speed) of the UAVs. The perceived noise of the aircraft depends on the generated noise, distance and environmental effects. For example, 120 dB noise of a jet engine decreases to 36 dB when it travels 55,000 feet. However, if this (~ 16km) distance is vertical than the air pressure, temperature and humidity effects the perceived noise levels and future studies are needed to improve the accuracy of estimations. Related equations are presented in the Appendix.

The most of the existing UAVs have been developed for military purposes. The noise was considered only to avoid detection of the system. The electric motors and well-designed propellers satisfied the needs for the small UAVs when they flew at the low altitudes. However, with the commercialization of the current UAV technology, current

noise regulations should be considered by the UAV designers. The agencies should come up with new ones by considering UAVs.

VI. CONCLUSION

The source of noise and noise reduction techniques for both airplanes and UAVs have been reviewed in this study. The ongoing regulatory developments were outlined to emphasize the importance of this issue for future manned or unmanned air vehicles.

UAVs have been used for military purposes and demonstrated their impressive potential at many applications such as surveillance, tracking targets and destroying them. They have tremendous potential in civilian applications and many people will be using them with different applications as soon as their commercial use becomes legal. To minimize their negative impact on humans and environment different aspects of their operation has to be considered. In this paper the noise is considered. Although, the size and power of the propulsion systems of the UAVs are typically smaller than the commercial aircraft, the UAVs operate at lower altitudes and may be used to scan a small area for many hours in many commercial applications. Their designers should consider the noise and take proper actions to keep it below acceptable levels.

APPENDIX

Three equations are provided here to emphasize the influence of the density of air on the speed, impedance and the energy flux of the sound waves.

Calculation of the sound energy flux "J":

$$J = (P^2 A / \rho v) \cdot \cos \theta \quad (1)$$

Where, " ρ " medium density, " v ", propagation velocity, " A " the area, " P " effective sound pressure.

For example a sound at 85 dB or 0.356 Pascal in air ($\rho = 1.2 \text{ kg/m}^3$; $v = 343 \text{ m/s}$; $A = 1 \text{ m}^2$; $\cos \theta = 1$) has a sound energy flux of 0,3 mW.

Calculation of the acoustic impedance "Z":

$$Z = \rho \cdot v \quad (2)$$

Where, " ρ " density of air is 1.2 kg/m^3 at 20°C in the sea level of 1 atmosphere where the speed of sound " v " is 343.21 m/sec and the acoustic impedance becomes 413.3 N.s/m^3 . Acoustic impedance and density of air are both dictate the speed of sound.

Calculation of the acoustic impedance " v ":

$$v^2 = \gamma \cdot R \cdot T / M \quad (3)$$

The speed of sound " v " varies by the altitude. Where the value of the humidity, the temperature as well as the molecular weight of the gases fluctuates by the altitude in the atmosphere. The " R " is molar gas constant; " γ " is adiabatic index, " T " is absolute temperature in Kelvin, and " M " is a molar mass.

REFERENCES

- [1] I. N. Tansel, G. Singha, G. Singh, S. Korla, M. Li, B. Uragun, *et al.*, "Genetically Optimized Neural Network Systems Applications for Unmanned Vehicles," in *International Unmanned Vehicles Workshop*, Istanbul, Turkey, 2010, pp. 230-233.
- [2] M. Dudek, P. Tomczyk, P. Wygonik, M. Korkosz, P. Bogusz, and B. Lis, "Hybrid Fuel Cell-Battery System as a Main Power Unit for Small Unmanned Aerial Vehicles (UAV)," *International Journal Electrochemical Science*, vol. 8, pp. 8442-8463, 2013.
- [3] O. Gonzalez-Espasandin, T. J. Leo, and E. Navarro, "Fuel Cells: A Real Option for Unmanned Aerial Vehicles Propulsion," *The Scientific World Journal*, vol. 2014, p. 12, 11 November 2013.
- [4] D. Verstraete, J. R. Harvey, and J. L. Palmer, "Hardware-in-the-loop simulation of fuel-cell-based hybrid-electrical UAV propulsion," in *28th International Congress of the Aeronautical Sciences*, 2012.
- [5] H. Fletcher and W. A. Munson, "Loudness, Its Definition, Measurement and Calculation," *The Journal of the Acoustical Society of America*, vol. 5, pp. 82-108, 1933.
- [6] G. International Organization for Standardization, Switzerland "Contours, Acoustics-Normal Equal-Loudness-Level International Standard ISO 226: 2003," in *TC/SC: ISO/TC 43, Stage: 90.60 (2013-09-18), ICS: 13.140, Edition: 2 (Monolingual)*, 2003, p. 18.
- [7] C. L. Wylie, "Supplemental environmental assessment for the potential upgrade of the Tenaska site for establishing a simple-cycle or combined-cycle electric generation facility," Tennessee Valley Authority, Haywood County, Tennessee, August 2008.
- [8] K. Servick, "Eavesdropping on Ecosystems," *Science*, vol. 343, pp. 834-837, February 21, 2014.
- [9] E. W. Vinje and E. T. Pitkin, "Human Operator Dynamics for Aural Compensatory Tracking," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. SMC-2, pp. 504-512, 1972.
- [10] K. Amanda, L. N. Richard, D. L. Ben, and H. R. Angus, "A Materiel Solution to Aircraft Upset," in *AIAA Guidance, Navigation, and Control Conference*, ed: American Institute of Aeronautics and Astronautics, 2014.
- [11] D. J. McDowall, "Planning on Noise: The Implementation of Noise Compatibility Zoning in the Northeast United States," MSc MSc, Graduate School of Architecture, Planning and Preservation, Columbia University, New York, NY, USA, 2012.
- [12] P. M. Rabinowitz, "Is noise bad for your health?," *The Lancet*, vol. 365, pp. 1908-1909, // 2005.
- [13] P. E. Brookhouser, "Prevention of Noise-Induced Hearing Loss," *Preventive Medicine*, vol. 23, pp. 665-669, 1994.
- [14] E. A. M. Franssen, C. M. A. G. van Wiechen, N. J. D. Nagelkerke, and E. Lebrecht, "Aircraft noise around a large international airport and its impact on general health and medication use," *Occupational and Environmental Medicine*, vol. 61, pp. 405-413, 1 May 2004.
- [15] M. M. Haines, S. A. Stansfeld, R. S. Job, B. Berglund, and J. Head, "Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children," *Psychological medicine*, vol. 31, pp. 265-277, 2001.
- [16] S. A. Stansfeld, B. Berglund, C. Clark, I. Lopez-Barrio, P. Fischer, E. Öhrström, *et al.*, "Aircraft and road traffic noise and children's cognition and health: a cross-national study," *The Lancet*, vol. 365, pp. 1942-9, 2005.
- [17] G. W. Evans and L. Maxwell, "Chronic Noise Exposure and Reading Deficits The Mediating Effects of Language Acquisition," *Environment and Behavior*, vol. 29, pp. 638-656, 1997.
- [18] M. Klatte, K. Bergstroem, and T. Lachmann, "Does noise affect learning? A short review on noise effects on cognitive performance in children," *Frontiers in psychology*, vol. 4, 2013.
- [19] W. Passchier-Vermeer and W. F. Passchier, "Noise exposure and public health," *Environmental health perspectives*, v. 108, p. 123, 2000.
- [20] L. Jarup, W. Babisch, D. Houthuijs, G. Pershagen, K. Katsouyanni, E. Cadum, *et al.*, "Hypertension and exposure to noise near airports: the HYENA study," *Environmental health perspectives*, vol. 116, p. 329, 2008.
- [21] H. Miedema and C. Oudshoorn, "Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals," *Environmental health perspectives*, vol. 109, p. 409, 2001.
- [22] B. Berglund, T. Lindvall, and D. H. Schwela, "Guidelines for community noise," in *Guidelines for community noise*, ed: OMS, 1999.
- [23] C. H. Hansen, "Fundamentals of acoustics," in *Occupational Exposure to Noise: Evaluation, Prevention and Control*. World Health Organization, Geneva, Swiss, 2001.
- [24] I. Secretariat, "ICAO's Balanced Approach to Aircraft Noise Management Noise at Source," International Civil Aviation Organization, Montreal, Quebec, Canada, 2007.
- [25] NASA-Facts, "Making Future Commercial Aircraft Quieter: Glenn Effort will Reduce Engine Noise," NASA, Glenn Research Center, Cleveland, OH, USA, July 1999.
- [26] C. Valdes, "Comparing methodologies that correlate property values and airport noise," MSc, Geography, San Jose State University, San Jose, CA, USA, 2008.
- [27] J. Xi, "A Research Assessment Report on Integrated Technology Demonstration & the Role of Public Policy," Ryerson Institute for Aerospace Design and Innovation, 13 July 2012.
- [28] R. D. Joslin, R. H. Thomas, and M. M. Choudhari, "Synergism of flow and noise control technologies," *Progress in Aerospace Sciences*, vol. 41, pp. 363-417, 2005.
- [29] E. Envia, "Emerging Community Noise Reduction Approaches," in *3rd Atmospheric and Space Environments Conference*, Honolulu, Hawaii, USA, 2011.
- [30] J. Mendoza, T. Brooks, and W. Humphreys, "An aeroacoustic study of a leading edge slat configuration," *International Journal of Aeroacoustics*, vol. 1, pp. 241-274, 2002.
- [31] C. J. Doolan, D. J. Moreau, and L. A. Brooks, "Wind turbine noise mechanisms and some concepts for its control," *Acoustics Australia*, vol. 40, 2012.
- [32] R. Tonin, "Sources of wind turbine noise and sound propagation," *Acoustics Australia*, vol. 40, 2012.
- [33] C. Doolan, "A Review of Wind Turbine Noise Perception, Annoyance & Low Frequency Emission," *Wind Engineering*, v. 37, pp. 97-104, '13.
- [34] A. Sutin, H. Salloum, A. Sedunov, and N. Sedunov, "Acoustic detection, tracking and classification of Low Flying Aircraft," in *International Conference on Technologies for Homeland Security*, 2013, pp. 141-146.
- [35] F. H. de Mendonça, "Structural optimization in acoustic radiation," MSc, Aerospace Engineering, Technical University of Lisbon, Portugal, 2007.
- [36] M. J. Doty, C. R. Fuller, N. H. Schiller, and T. L. Turner, "Active Noise Control of Radiated Noise From Jets," NASA, Langley Research Center, Hampton, Virginia, USA, 2013.
- [37] C. R. Fuller, S. D. Snyder, C. H. Hansen, and R. J. Silcox, "Active control of interior noise in model aircraft fuselages using piezoceramic actuators," *AIAA Journal*, vol. 30, pp. 2613-7, 1992.
- [38] J. Jaworski and N. Peake, "Vortex Noise Reductions from a Flexible Fiber Model of Owl Down," in *Bulletin of the American Physical Society, 66th Annual Meeting of the APS Division of Fluid Dynamics* David L. Lawrence Convention Center in Pittsburgh, Pennsylvania, USA, 2013.
- [39] L. Shi, W. Q. Wang, C. C. Zhang, J. Wang, and L. Q. Ren, "The Effect of Bionic V-Ring Surface on the Aerodynamic Noise of a Circular Cylinder," *Applied Mechanics and Materials*, vol. 461, pp. 751-62, '14.
- [40] D. S. Miklosovic, M. M. Murray, L. E. Howle, and F. E. Fish, "Leading-edge tubercles delay stall on humpback whale (Megaptera novaeangliae) flippers," *Physics of Fluids (1994-present)*, vol. 16, pp. L39-L42, 2004.
- [41] N. Canter, *Humpback whales inspire new wind turbine technology* vol. 64. Park Ridge, IL, ETATS-UNIS: Society of Tribologists and Lubrication Engineers, 2008.
- [42] F. E. Fish, P. W. Weber, M. M. Murray, and L. E. Howle, "The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology," *Integrative and Comparative Biology*, vol. 51, pp. 203-213, July 1, 2011.
- [43] X. Jiang, B. Liang, X.-y. Zou, L.-l. Yin, and J.-c. Cheng, "Broadband field rotator based on acoustic metamaterials," *Applied Physics Letters*, vol. 104, pp. 083510 - 1:4, 2014.

- [44] S. Sullivan, "Method and apparatus for mitigating trailing vortex wakes of lifting or thrust generating bodies," ed: Google Patents, 2008.
- [45] C. S. Goguet, "Aero-acoustic optimisation method for complex-section mechanical parts and corresponding mechanical part and landing gear," ed: Google Patents, 2011.
- [46] X. P. Zhang, Y. H. Wang, and L. Q. Ren, "Wind Tunnel Test for Drag Reduction of Airfoil Bionic Soft Surface," *Applied Mechanics and Materials*, vol. 461, pp. 767-778, 2014.
- [47] H. C. Lester and C. R. Fuller, "Active control of propeller-induced noise fields inside a flexible cylinder," *AIAA Journal*, vol. 28, pp. 1374-1380, 1990.
- [48] G. A. Bres, F. E. Ham, J. W. Nichols, S. K. Lele, and J. T. Spyropoulos, "Massively-Parallel Simulations of Supersonic Jet Noise from Complex Nozzles," 2013.
- [49] D. Papamoschou and R. S. Shupe, "Effect of nozzle geometry on jet noise reduction using fan flow deflectors," in *12th AIAA/CEAS Aeroacoustics Conference (27th AIAA Aeroacoustics Conference)*, Cambridge, Massachusetts, USA, 2006, pp. 8-10.
- [50] H. E. Hafsteinsson, L.-E. Eriksson, N. Andersson, D. R. Cuppoletti, E. Gutmark, and E. Prisell, "Supersonic Jet Noise Reduction Using Steady Injection and Flapping Injection," in *19th AIAA/CEAS Aeroacoustics Conference*, Berlin, Germany, 2013.
- [51] J. W. Nichols, S. K. Lele, F. E. Ham, S. Martens, and J. T. Spyropoulos, "Crackle Noise in Heated Supersonic Jets," *Journal of Engineering for Gas Turbines and Power*, vol. 135, pp. 051202-051202, 2013.
- [52] M. Vanhoecke, "Active control of sound for improved music experience," MSc, Department of Information Technology, Ghent University, 2013.
- [53] Z. JunHong and H. Bing, "Analysis of engine front noise using sound intensity techniques," *Mechanical Systems and Signal Processing*, vol. 19, pp. 213-221, 1/ 2005.
- [54] W. Neise and L. Enghardt, "Technology approach to aero engine noise reduction," *Aerospace Science and Technology*, v. 7, pp. 352-63, 2003.
- [55] D. Hammond, R. McKinley, and B. Hale, "Noise Reduction Efforts for Special Operations C-130 Aircraft Using Active Synchrophaser Control," DTIC Document, AFRL, Wright Patterson, AFB OH, USA1998.
- [56] D. Blunt and B. Rebbechi, "An investigation into active synchrophasing for cabin noise and vibration reduction in propeller aircraft," in *The ACTIVE 2006 Institute of Noise Control Engineering, 6th International Symposium on Active Noise and Vibration Control*, Adelaide, SA, Australia, 2006.
- [57] R. Makarewicz, "Prediction of noise reduction through vehicle path rerouting," *The Journal of the Acoustical Society of America*, vol. 127, pp. 216-222, 2010.
- [58] N. Nijhawan and H. Wesoky. (2014, 6 March). "Environment: Aircraft Noise Reduction" by NASA Headquarters Responsible Official: Code R; Curator: SAIC Information Services. Available: <http://www.aeronautics.nasa.gov/docs/chicago/noise.htm>
- [59] DoD, "Noise Program," in *Instruction 4715.13*, ed. USA: Department of Defence, 2005.
- [60] D. Sari, N. Ozkurt, A. Akdag, M. Kutukoglu, and A. Gurarslan, "Measuring the levels of noise at the İstanbul Atatürk Airport and comparisons with model simulations," *Science of The Total Environment*, vol. (article in press), 2013.
- [61] R. H. Lyon, "Propagation of Environmental Noise," *Science*, vol. 179, pp. 1083-1090, March 16, 1973.
- [62] M. Zhou and J. V. R. Prasad, "Transient characteristics of a fuel cell powered UAV propulsion system," in *International Conference on Unmanned Aircraft Systems*, Atlanta GA, USA, 2013, pp. 114-123.
- [63] J. Yang, J. Chen, Y. Liu, W. Yang, Y. Su, and Z. L. Wang, "Triboelectrification-Based Organic Film Nanogenerator for Acoustic Energy Harvesting and Self-Powered Active Acoustic Sensing," *ACS Nano*, 2014.
- [64] S. Korla, "Inspection of Parts with Complex Geometry and Welds with Structural Health Monitoring Techniques," PhD PhD, Mechanical Engineering, Florida International University, Miami, 2011.
- [65] P. Chudy and P. Rzućidło, "Real-time simulations of environmentally friendly flight control system," in *IEEE 9th International Symposium on Applied Machine Intelligence and Informatics*, Smolenice, Slovakia, 2011, pp. 161-164.
- [66] Y. Park, K. J. McDonald, and K.-S. Choi, "Progress in bismuth vanadate photoanodes for use in solar water oxidation," *Chemical Society Reviews*, vol. 42, pp. 2321-2337, 2013.
- [67] J. A. Seabold and K.-S. Choi, "Efficient and Stable Photo-Oxidation of Water by a Bismuth Vanadate Photoanode Coupled with an Iron Oxyhydroxide Oxygen Evolution Catalyst," *Journal of the American Chemical Society*, vol. 134, pp. 2186-2192, 2012.
- [68] T. W. Kim and K. S. Choi, "Nanoporous BiVO₄ Photoanodes with Dual-Layer Oxygen Evolution Catalysts for Solar Water Splitting," *Science (New York, N.Y.)*, 02/ 2014.
- [69] F. F. Abdi, L. Han, A. H. Smets, M. Zeman, B. Dam, and R. van de Krol, "Efficient solar water splitting by enhanced charge separation in a bismuth vanadate-silicon tandem photoelectrode," *Nature communications*, vol. 4, 29 July 2013.
- [70] K. Willquist, A. A. Zeidan, and E. W. van Niel, "Physiological characteristics of the extreme thermophile *Caldicellulosiruptor saccharolyticus*: an efficient hydrogen cell factory," *Microb Cell Fact*, vol. 9, p. 89, 2010.
- [71] A. Melis and T. Happe, "Hydrogen Production. Green Algae as a Source of Energy," *Plant Physiology*, vol. 127, pp. 740-748, 2001.
- [72] I. K. Kapdan and F. Kargi, "Bio-hydrogen production from waste materials," *Enzyme and Microbial Technology*, vol. 38, pp. 569-582, 2006.
- [73] H. M. G. Vidales, "Design, Construction and Test of the Propulsion System of a Solar UAV," MSc, Aerospace Engineering, Technical University of Lisbon, 2013.
- [74] B. Lee, P. Park, C. Kim, S. Yang, and S. Ahn, "Power managements of a hybrid electric propulsion system for UAVs," *Journal of Mechanical Science and Technology*, vol. 26, pp. 2291-2299, 2012.
- [75] Y. Li, L. Liu, X. Ma, and H. Tu, "Design of Hybrid Electric Propulsion System for Long Endurance Small UAV," in *10th International Energy Conversion Engineering Conference*, 2012.
- [76] R. Andriani, A. Ingenito, F. Gamma, and A. Agresta, "Low-Fuel Consumption Gas Turbine Engines for Extended-Range UAVs," in *AIAA SciTech, 52nd Aerospace Sciences Meeting*, National Harbor, Maryland, USA, 2014.
- [77] J. Koster, C. Humbargar, E. Serani, A. Velazco, D. Hillery, D. Larrabee, et al., "Hybrid Electric Integrated Optimized System (HELIOS): Design of a Hybrid Propulsion System for Aircraft," in *49th AIAA Aerospace Sciences Meeting*, Orlando, FL, USA, 2011.
- [78] G. Sinibaldi and L. Marino, "Experimental analysis on the noise of propellers for small UAV," *Applied Acoustics*, vol. 74, pp. 79-88, 13.
- [79] O. Gur and A. Rosen, "Optimizing electric propulsion systems for unmanned aerial vehicles," *Journal of aircraft*, vol. 46, pp. 1340-1353, August 2009.
- [80] A. Ravi, "UAV Power Plant Performance Evaluation," MSc, Mechanical Engineering, Oklahoma State University, 2010.

The selection of UAVs propulsion system	ENGINE WEIGHT	POWER TO WEIGHT RATIO	EFFICIENCY	SPECIFIC PROPULSIVE ENERGY DENSITY	REMARK
Two-strokes	Good	High	Low	Good	Noise issue, worse than four-stroke and Wankel
Four-strokes	Too heavy	Better than two-stroke	High	Good	Noise issue
Wankel	Better than two & four-strokes	Low	Low	Not good as two & four - strokes	High pollutant at high RPM
Turbine	Lighter than four-strokes and Wankel	Highest	Low	Low	Noise issue
Electric	Good	Good	Highest	Low	Less pollutant with high RPM

Table 1: Recent UAVs' propulsion technologies are compared for advantages and disadvantages. The total of 71 different propulsion systems (5 – 100 Horse power) are tested in five groups (33 of two-strokes, 15 of four-strokes combustion engines, with five Wankel, six turbines and 12 electric motors) summarized from [80].