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AIRCRAFT NOISE MODELLING AND 4D TRAJECTORY OPTIMISATION METHODS FOR REDUCED ENVIRONMENTAL IMPACTS AT AIRPORTS

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SUMMARY

The combined requirements of Air Traffic Management (ATM) research initiatives (SESAR and NextGen) and environmentally sustainable aviation programmes (Clean Sky and Environmentally Responsible Aviation) aim at lowering operating costs and reducing noise and gaseous emissions. Aircraft noise modelling in airports around the globe is essential in order to comprehend the noise impacts associated with air traffic, and determining the noise footprints so that effective airport planning strategies can be implemented. The methodology of adopting aircraft noise modelling techniques in conjunction with Demographic Distribution Database (D^3) and Digital Terrain Elevation Database (DTED) that allows for the development of a novel approach towards aircraft noise mitigation in the present and likely future airspace and airport scenarios is presented. The Four Dimensional (4D) aircraft intents are optimised to minimize the effects of noise, specifically targeted around densely populated areas.

Keywords: Aircraft Noise, Environmentally Sustainable Aviation, 4D Trajectory, Trajectory Based Operations, Trajectory Optimisation.

INTRODUCTION

In order to cater for the predicted growth rates of air traffic and the associated passenger volumes, airports have undertaken substantial redevelopment actions to enhance infrastructure and services for air travel (Airbus, 2013)(Ashford et al., 2013). Political and research initiatives involving airport greening increase the environmental awareness and cost-effectiveness through the integration of new technologies that require less energy. A number of global and regional research initiatives are addressing the mitigation of aircraft noise emissions. The Single European Sky Air Traffic Management Research (SESAR) and the Clean Sky Joint Technological Initiative (JTI) for Aeronautics and Air Transport are the major programmes developing and implementing innovative concepts for future air transportation in Europe (EU, 2014, JU, 2011). In parallel the Next Generation Air Transportation System (NextGen) programme and the Environmentally Responsible Aviation (ERA) project by the National Aeronautics and Space Administration (NASA) are driving the modernisation process in the United States (FAA, 2013, Nickol, 2011). The Advisory Council for Aeronautics Research and Innovation in Europe (ACARE) for aircraft has identified ambitious goals including the reduction of perceived external noise by 65% (ACARE, 2008, ACARE, 2012). Synergies between the SESAR and NextGen concepts of operations are currently studied and one such programme is the Atlantic Interoperability Initiative to Reduce Emissions (AIRE), which aims at enhancing energy efficiency, and reducing aircraft engine emissions and noise by through various research activities (Hotham, 2011, Nieuwenhuisen and de Gelder, 2012, Reynolds et al., 2010). Australian initiatives for sustainability are aligned with those of the Asia-Pacific region with Australia's involvement in the Asia and South Pacific Initiative to Reduce Emissions (ASPIRE) programme (Hayman, 2009, Shresta et al., 2009). Research results have shown that improvements in the Flight Management System (FMS) and ATM software can directly contribute to noise abatement and help in reducing aircraft engine emissions (ICAO, 2010, Oxford, 2010). In order to mitigate the impacts related to aircraft noise, the 33rd meeting of the International Civil Aviation Organization (ICAO) adopted the A33/7 Resolution, conceiving a balanced approach to noise and emission reductions. A number of countries in the world have adopted these guidelines aiming for a better control and mitigation of airport noise and its associated effects on the communities in the vicinity of airports. Noise reduction at source, land use planning, operational procedures and restrictions are a few key noise mitigation strategies (Heleno et al., 2014).

AIRCRAFT NOISE MODELLING

The noise produced by aircraft around airports represents an ecological, economic, operational and social problem and affects specifically the communities in the proximity of airports and densely populated areas (Upham, 2003, Whitelegg, 2000). The number of noise sources of an aircraft differs with respect to its type and the propulsion system. The three main components of aircraft noise are aerodynamic, propulsive and noise from other mechanical, thermochemical and fluid dynamic processes. Generally, the atmosphere acts as a low pass filter for the noise propagation spectrum, due to thermo-fluid-dynamics and molecular processes. The perceived noise level depends on a number of factors including individual listener's cultural and socio-economic background as well as their psychological and physical situation. The effects of aircraft noise vary from no influence, to minor annoyance, to even potential health hazards (Franssen et al., 2004). Generally noise from departing aircraft is greater than that of an arriving aircraft due to the relatively gentle approach glide slope of 3°, involving limited engine noise (Filippone, 2014). On a departure, the noise level experienced on the ground from a particular aircraft is influenced by the aircraft type, size, Standard Instrument Departure (SID) used, aircraft settings, climb rate and the meteorological conditions. The relationship between the acoustic characteristics of the primary and secondary noise sources and the flight mode parameters must be determined to estimate the noise levels. Planning, evaluation and development (design and redesign) of airports are dependent on the noise measurements around the airport. The diversity of aircraft types, flight procedures and propulsive systems, leading to large datasets, increase the complexity of the noise contour determination process. The measurement of aircraft noise at airports may involve several metrics including A-Weighted Sound Exposure Level (SEL / LAE) and Effective Perceived Noise Level (EPNL / LEPN) (Müller and Möser, 2013).

4D TRAJECTORY OPTIMISATION FOR NOISE MITIGATION

Aircraft noise guidelines have been developed by national or international aviation organisations including the ICAO guidance in its Circular 205, the Society of Automotive Engineers (SAE) Committee A-21 and the European Union recommended use of the European Civil Aviation Conference - Conférence Européenne de l'Aviation Civile (ECAC-CEAC) Doc. 29 (ECAC.CEAC, 1997, ICAO, 1988, Quindry, 1976). In order to model aircraft noise generation and propagation, progressive sound wave traveling in a plane is considered. The rate of transfer of energy per unit cross-sectional area for the sound wave is defined as Sound Intensity (SI) and is given by:

$$SI = \frac{1}{T}\int_0^T p\ u\ dt \qquad (1)$$

where p is the instantaneous acoustic pressure and u is the particle velocity of the wave. Total Intensity produced by several sources is given by:

$$SI = S\,I_1 + SI_2 + SI_3 + \ldots \qquad (2)$$

The generation and propagation of aircraft noise through the atmosphere are the essential aspects for aircraft trajectory optimisation. The optimiser needs to include a model of aircraft noise to allow the minimisation of perceived noise on the ground. In order to generate an optimal trajectory, the Integrated Noise Model (INM) from the Federal Aviation Administration (FAA) is generally adopted as reference. Noise is calculated based on interpolation of data specified in the Noise-Power-Distance (NPD) table containing empirical measurements for each aircraft type under reference conditions. The INM model uses a grid-based approach and a number of metrics including exposure-based, maximum noise level and time-based are adopted (Boeker et al., 2008). In order to critically evaluate the noise levels, the Aviation Environmental Design Tool (AEDT) developed by the FAA, serves as a multi-purpose framework integrating the INM and the Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA), a global noise model (Noel et al., 2009). The overall sound level L is given by:

$$L = 10\ log_{10}\left(\sum_{i=1}^{n} 10^{L_i}\right) \qquad (3)$$

where L is the sum of n noise levels L_i all at the same frequency. The sensitivity due to perturbation on the sound level dL_i on the sound levels L_i of n contributes is given by (Filippone, 2014):

$$L + dL = 10\ log_{10}\left(\sum_{i=1}^{n} 10^{(L_i + dL_i)/10}\right) \qquad (4)$$

The concept of noise-radius is adopted generally by considering the complexity of aircraft noise based on aircraft engine type, thrust setting and atmospheric conditions (Zaporozhets et al., 2011). The optimisation of aircraft vertical trajectory with minimum noise impact using analytical jet noise model has proved to be effective (Khardi and Abdallah, 2012). The methodology adopted requires demographic data at each observer location and hence a Demographic Distribution Database (D^3) is used in conjunction with the noise model. The D^3 model aids in estimating the population in a user defined grid in a global or local scale. Additionally, the Digital Terrain Elevation Database (DTED) is also employed to define the exact spatial position of ground observer locations. The availability of D^3 and DTED are specifically important for assessing environmental impact of aircraft noise in the Terminal Maneuvering Area (TMA). Four Dimensional (4D) trajectory optimisation is generally performed to avoid the densely populated areas in and around the airports taking into account the topographical conditions, metrological data and path constraints. The path constraints can be operational, airspace, airline, flight parameters and/or aircraft performance. Several optimization studies have been carried out for the aircraft trajectory based on a number of cost functions such as number of sleep disturbances resulting in reduction of noise annoyance on specific regions around an airport (Camilleri et al., 2012, Chircop et al., 2012, Cooper et al., 2012, Gauci et al., 2012, Gu et al., 2012, Navaratne et al., 2012, Pisani et al., 2013, Sammut et al., 2012). Reduced noise procedures implemented are Noise Abatement Departure Procedures (NADP) including NADP1, NADP2, its associated variations, and ICAO-A (Filippone, 2014). Steep trajectory approach, spiral trajectories and touch-down displacement principles have been proposed and trialled to reduce noise while landing. Generally, the noise minimisation is conflicting with the minimisation of fuel consumption and other environmental emissions (Prats et al., 2011, Torres et al., 2011). Hence a multi-disciplinary, multi-objective and multi-model approach is required (Gardi et al., 2013, Gardi et al., 2014, Ramasamy et al., 2014, Ramasamy et al., 2013). Fig. 1 illustrates the trajectory optimisation process specific to noise mitigation. The cost J for noise can be expressed in relation to the state vector, $X(t)$ and control vector, $V(t)$ as:

$$J[t, X(t), V(t)] = 10\, log_{10}\left(\sum_{i=1}^{n} 10^{L_{Amax_i}/10}\right) \quad (5)$$

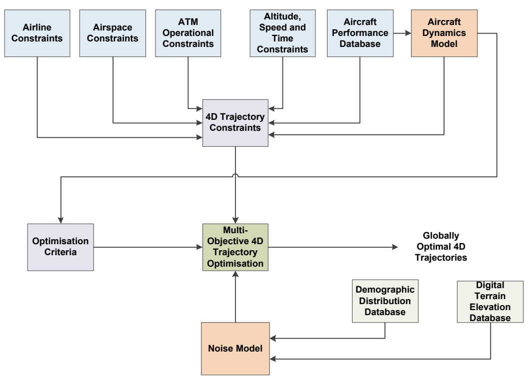

Fig. 1. 4D Trajectory optimization for noise mitigation.

The impact of perceived noise on the population is commonly described by dose-response relationships. Awakening Index (AI) defined by the percentage of persons awakened at a specific location as a function of perceived indoor SEL is given by:

$$\text{AI} = 0.0087\,.\,(SEL_{indoor} - 30\text{ dB})^{1.79} \quad (6)$$

The indoor SEL is estimated from the outdoor SEL by subtracting 20.5 dB (average loss due to the sound insulation of a typical house).

The number of awakenings for a specific noise station is calculated by multiplying the percentage of awakenings of the station i with the population P_i assigned to that receiver.

$$n_{awakenings} = \sum_{i=1}^{n} \%awakenings_i\,.\,P_i \quad (7)$$

NOISE MANAGEMENT

The European Directive 2002/30/EC defines the concept of noise management as a balanced approach wherein international aviation organisations, Governments, aircraft manufacturers, airliner and airport operators focus on the following key areas (EU, 2002, Licitra et al., 2014, Stevens et al., 2010):

- Reduction of noise at the source through aircraft technology improvements.
- Compatible land-use planning.
- Increased adoption of noise abatement procedures.
- Optimisation of the aircraft engine setting and trajectories to avoid the Noise-Sensitive Areas (NSA).
- Introduction of operating restrictions.

A typical aircraft noise mitigation scenario is considered in Fig. 2 in which probable 4D intents are obtained so that the overflight of densely populated areas is avoided. Fig. 3 shows a MATLAB™ simulation result for the scenario illustrated in Fig. 2 when an aircraft departing London Heathrow airport avoids two NSA.

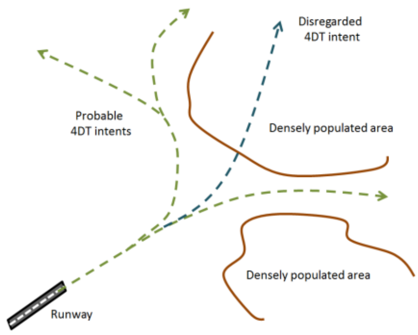

Fig. 2. Scenario for simulation.

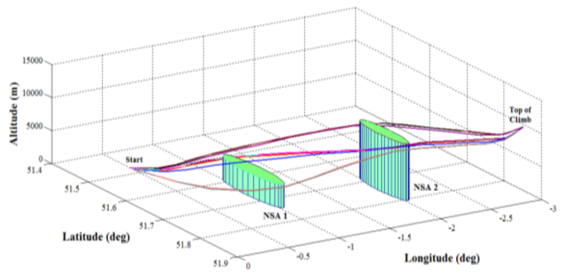

Fig. 3. 4DT intents avoiding NSA.

The ICAO Committee on Aviation Environmental Protection (CAEP) agreed to set new standards on noise reduction worldwide (ICAO 2013). According to FAA, the most promising aspect is technology development to reduce the noise at source. The Continuous Lower Energy, Emission and Noise (CLEEN) programme is an ongoing program implemented to advance the development of technologies to further reduce noise from aircraft (FAA 2014). The major aim of the CLEEN program is to help and develop certifiable aircraft technology that reduces noise levels by 32dB cumulative, relative to the ICAO noise standards (FAA 2014).

CONCLUSIONS

A number of efforts are currently undertaken by international aviation organisations, airlines, airports, aircraft manufacturers and Governments to address the environmental effects caused by aviation. In line with the requirements defined by the policy makers and sustainability programmes, the reduction of environmental impacts including aircraft noise in and around airports is considered as one of the key elements in mitigating the detrimental effects. The primary and secondary sources of aircraft noise and the various measurement metrics used for quantification purposes were discussed. The noise modelling approaches and algorithms for aircraft trajectory optimisation were presented. Noise monitoring and management measures were addressed. In future studies, efforts are required to further develop noise mitigation strategies to better protect the communities around airports, legalisation measures and improved noise abetment procedures.

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