Transportation Research Part C 18 (2010) 975–989

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

# Multi-objective optimisation for aircraft departure trajectories minimising noise annoyance

Xavier Prats [a,*], Vicenç Puig [b], Joseba Quevedo [b], Fatiha Nejjari [b]

[a] Technical University of Catalonia (UPC), Polytechnic School of Castelldefels (EPSC), PMT Office C3-104, Esteve Terradas, 5, 08086 Castelldefels, Spain
[b] Technical University of Catalonia (UPC), Automatic Control Department (ESAII), Rambla St. Nebridi 10, 08222 Terrassa, Spain

ARTICLE INFO

*Article history:*
Received 26 August 2008
Received in revised form 28 August 2009
Accepted 3 March 2010

*Keywords:*
Aircraft noise abatement procedures
Noise annoyance
Multi-objective optimisation
Fuzzy logic

ABSTRACT

This paper presents a strategy for designing noise abatement procedures aimed at reducing the global annoyance perceived by the population living around the airports. A non-linear multi-objective optimal control problem is implemented and numerically solved obtaining minimal annoyance trajectories. Annoyance criteria are treated as non-linear functions that can be obtained by using fuzzy logic modelling techniques. Here, a basic implementation is shown where the annoyance is expressed in function of the maximum perceived noise level, the period of the day when the trajectory takes place and the type of area over-flown. Then, lexicographic optimisation techniques are used to deal with the multi-criteria nature of the problem. Finally, an illustrative example is given concerning a hypothetical scenario with five different noise sensitive locations and where different optimal trajectories are obtained for different hours of the day.



## 1. Introduction

The noise produced by aircraft during take-off and landing operations is becoming a very serious ecological and social problem. Aircraft noise can be very annoying for people living in the vicinity of the airports. Therefore, the design of noise abatement procedures aimed at reducing the noise exposure of the affected population is one of the main issues that airport authorities and air navigation service providers have to address.

Noise is generally defined as an unwanted sound and its effects can be appreciated physiologically but also psychologically. See, for instance, the work done by Muzet (2007). On the other hand, annoyance is a concept that is hard to quantify because there is no underlying physically measurable scale. However, it is usually qualitatively assessed with social surveys. It is clear that *fuzzy logic* techniques can help to make more accurate predictions by incorporating the vagueness and uncertainty into the modelling and reasoning process. Fuzzy set theory is a generalisation of traditional set theory and provides a means for the representation of imprecision and vagueness. Zadeh (1965) further developed the corresponding fuzzy logic to manipulate fuzzy sets. Recently, some research papers based on fuzzy logic have addressed noise pollution topics: see, for instance the works published by Botteldooren and Verkeyin (2003), Zaheeruddin et al. (2006) or Zaheeruddin and Vinod (2006). For example, Zaheeruddin et al. (2006), consider the annoyance as a function of the noise level, its duration of occurrence, and the socioeconomic status of a person, applying these models to the urban areas of India. Moreover, Zaheeruddin and Vinod (2006) present a fuzzy logic model based on field surveys conducted by various researchers and reports of the

* Corresponding author. Tel.: +34 93 413 41 25; fax: +34 93 413 70 07.
*E-mail addresses:* xavier.prats@upc.edu (X. Prats), vicenc.puig@upc.edu (V. Puig), joseba.quevedo@upc.edu (J. Quevedo), fatiha.nejjari@upc.edu (F. Nejjari).

0968-090X/$ - see front matter 
doi:10.1016/j.trc.2010.03.001

World Health Organisation. There, it is shown how the noise level, the duration of the acoustical event and the age of the exposed people affect on the sleep disturbance.

On the other hand, the International Civil Aviation Organisation (ICAO) publishes two different Noise Abatement Departure Procedures (NADP), defined in ICAO (1993). NADP are generic procedures and are far from being the optimum ones regarding noise minimisation. This is due to several factors, such as the impossibility to define a general procedure satisfying the specific problems that may affect each particular airport, air traffic management and airport capacity constraints or even the limitations of nowadays on-board technology. Nevertheless, some research in theoretical optimal trajectories minimising the noise impact in departure or approaching procedures is also found in the literature. For instance, Visser and Wijnen (2001) presented a tool combining a noise computation model, a Geographical Information System (GIS) and a dynamic trajectory optimisation algorithm, aimed at obtaining optimal noise procedures. See also Wijnen and Visser (2003) and Visser (2005). A similar methodology is proposed by Clarke and Hansman (1997), and an adaptative algorithm for noise abatement is also developed by Zou and Clarke (2003). On the other hand, Atkins and Xue (2004) and Xue and Atkins (2006) presented a dynamic programming technique for minimising noise in runway-independent aircraft operations. All the results and conclusions arisen from these works are encouraging and will set the basis for new noise abatement procedures, specially regarding the forthcoming new navigation concepts, such as area navigation (RNAV) or Performance Based Navigation (PBN). These concepts, as explained by EUROCONTROL (1999), will allow for air navigation procedures to be designed with a higher level of flexibility than conventional radionavigation ones.

This paper presents a methodology to design optimal aircraft trajectories by using a dynamic trajectory optimisation algorithm where only an initial and a final point in the trajectory are specified. It is shown how the optimisation criteria can easily be built from non-linear annoyance functions, which in turn, can be derived from more complex fuzzy logic models. In Section 2 the model for noise annoyance used in this work is presented, while in Section 3 the multi-criteria optimisation technique is described. Finally, Section 4 shows some illustrative and practical results for a hypothetical scenario.

## 2. A model for noise annoyance

The annoyance or perception of the acoustic noise describes the relation between a given acoustic situation and a given individual or set of persons affected by the noise and how cognitively or emotionally they evaluate this situation. Human perception of loudness is highly non-linear, and the relationship between frequency, intensity, and loudness is quite complex.

In order to take into account this particular human perception sound spectra measurements are usually modified when dealing with environmental noise by a weighting function (A – weighted decibel scale) and acoustical magnitudes are expressed in dB(A). Besides the frequency spectra, different ways of measuring a same acoustical event can be implemented. For example, a simple and widely used metric is to measure the maximum sound level ($L_{max}$) of the event. On the other hand, the Sound Exposure Level (SEL) metric takes into account not only the acoustical intensity but also the time duration of the event. Moreover, other metrics exist when one wants to consider the noise impact of several events during a certain period, like for example a day. The Equivalent Sound Level ($L_{eq}$) and the Day–Night Sound Level ($L_{dn}$) metrics are commonly used in aircraft noise surveys. For more noise metrics and their exact computations the reader could refer to Harris (1997) or FAA (2002).

As it can be seen, all metrics try to model the way the sound is perceived by humans. However, these metrics are not sufficient measurements defining completely the annoyance that a particular noise produces. In addition to acoustic elements such as the loudness, the intensity, the spectra and the duration, there is a list of non-acoustic elements that should be taken into account to define a global annoyance figure. According to Schomer (2001), Lim et al. (2007), Rylander (2004), Kuwano and Namba (1996) and Hume et al. (2003), one should consider the following most relevant factors:

- Types of affected zones (rural zone, residential zone, industrial zone, hospitals, schools, markets, etc.).
- Time interval during the noise event (day, evening, night).
- Period of time between two consecutive flights.
- Personal elements (emotional, apprehension to the noise, personal healthy, age, etc.).
- Cultural aspects (young or aged people habits, activities, holiday, etc.).

In this paper, a simplified fuzzy logic model describing aircraft noise annoyance is implemented, taking only into account the maximum perceived sound level ($L_{max}$), the hour of the day when the flight takes place and the type of over-flown zone, considering industrial and residential zones, a hospital and a school.

### 2.1. Noise model

The maximum perceived sound level ($L_i$) at a given location $i$ is defined as:

$$L_i(\boldsymbol{z}) = \max_t \; Noise_i(\boldsymbol{z}(t)) \qquad (1)$$

where $Noise_i(\boldsymbol{z}(t))$ is the perceived noise level at location $i$ for a given trajectory $\boldsymbol{z}(t)$ (being $t$ the time variable).