AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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MODELS OF QUALITATIVE ESTIMATION OF AIR TRAFFIC FLOWS AND CAPACITY IN TERMINAL CONTROL AREAS

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Abstract

Purpose: *The aim of this study is to research applied models of qualitative estimation of air traffic flow and capacity in terminal control area (TMA) under uncertainty conditions. In this work the theoretical framework descripting departing and arriving air traffic flows in order to regulate capacity and decrease delays in terminal control areas airspace is proposed.* ***Methods:*** *Optimisation of terminal control area formal description based on composite model of typical airspace elements and operational procedures, reduction of delays on runways and in the airspace in vicinity of aerodrome using the airport and terminal control area operations optimisation model, assessment of various types of uncertainties and associated factors by application of terminal control area queueing analysis uncertainty model.* ***Results:*** *Terminal control area descriptive model, airport and TMA operations optimisation model and TMA queueing analysis uncertainty model were obtained. Principles of estimating of quantitative parameters of air traffic flows and capacity in terminal control areas under uncertainty conditions were proposed.* ***Discussion:*** *Composite elements of terminal control area descriptive model, principles of delays reduction as a result of application of airport and TMA operations optimisation model and assessment of impact of uncertainty factors in air traffic control and flight operations by TMA queueing analysis uncertainty model.*

Keywords: aeronautical system; air traffic flows models; air traffic flow and capacity management; air traffic services; safety of flights; terminal control area descriptive model; uncertainty factors.

1. Introduction

Nowadays, delays and flight cancellations in air traffic management are the significant problems, which are mainly connected with capacity limits, particularly in Europe and Northern America where the flight volumes are high. Reducing of these delays and appropriate costs represents a significant challenge for the civil aviation industry and in particular Eurocontrol and Civil Aviation Authorities of European countries.

The air transportation in most of European, South East Asia and North America countries has reached saturation. The increase in air traffic flow results in traffic congestions in terminal control areas, which affects the optimal flight operation. TMA is considered as one of the most complicated portions of airspace, as far as it designed to operate aircraft arriving to and departing from airports using Standard Instrument Arrival routes (STARs) and Standard Instrument Departure routes (SIDs).

One of solutions how to reduce delays and cope with increased air traffic flows is to expand the air transportation infrastructure and provide efficient network management. However, it is very expensive and would take many years to successfully implement it.

Therefore, in order to reduce delays, optimizing departure and arrival procedures is vital to regulate air traffic flow in the vicinity of aerodrome taking into account a wide variety of contributing factors [1-3]. With reduced delays, shall also decrease negative impact on environment, as a result of reduced emissions, as well as it makes possible improved management of flight safety.

In the article we propose set of models devoted to qualitative estimation of air traffic flows and capacity in TMA under uncertainty conditions in flight.

2. Analysis of the latest research and publications

The air traffic flows and capacity management in TMA is an important and dynamic research area in Air Traffic Management (ATM), which regulated on international and national levels [4,5]. In [6], an optimization algorithm is proposed for designing departure and arrival routes at a strategic level in 3D, which is helpful for regulation of air traffic flows in TMA. The authors [6] propose method to design automatically the SIDs and STARs for a given TMA configuration, taking inti account number of entry/exit points, forbidden areas and significant operational constraints. The influence of fluctuating meteorological conditions on TMA operations performance studied in [7].

The airport operations optimization problem regarding co-ordination of TMA flights and aerodrome operations in a tractable and unified manner is discussed in [8]. This includes solving the air traffic flow and capacity management (ATFCM) problems faced at an airport, such as: selecting a runway configuration sequence, assigning flights to runways and determining the sequence in which flights are processed, determining the gate-holding duration of departures and routing flights to their assigned runway and onwards within the TMA and the near-terminal airspace.

Applied models of air traffic flows in TMA are considered in such works as: continuous flow Eulerian model for air traffic networks [9] to describe optimal control principles and alleviate airspace congestion through the optimal routing of flights; stochastic air traffic flow models [10] based on queuing network models; aggregate dynamic stochastic model for an air traffic system [11] and computer-aided Eulerian air traffic flow model [12,13]. These models allow taking into account a wide variety of uncertainties such as delays due to weather deviation, air traffic control actions, aircraft performance, navigation system precision and flight control. In [14, 15] the major problem of air traffic flow management under uncertainty is investigated in detail.

3. Terminal control area descriptive model

In the beginning, for quantitative analysis of air traffic flows in terminal control area, we need model which describes main elements, departure and arrival routes and technological operations (the air traffic controller activities) [6]. Let N be the total amount of flights arriving at and departing from the certain airport. Aircraft enters/exits the TMA on several predetermined fixes on borders $\Theta = \{O_1, \ldots, O_{n_{in}}, O_{n_{in}+1}, \ldots, O_{n_{in}+n_{out}}\}$, where the first n_{in} points are the entry points and the remaining n_{out} ones are exit points. Suppose that $\mathrm{I} = \{I_1, \ldots, I_{n_{arr}}, I_{n_{arr}+1}, \ldots, I_{n_{arr}+n_{dep}}\}$ is the set of arrival and departure points, where the first n_{arr} points are the arrival points and the remaining n_{dep} ones are departure points. As TMA is generally designed in a near circular configuration with airport control point in the centre, we assume it is composed of two concentric circles C_1 and C_2, with radius R_1 and R_2 respectively (Fig. 1).

The arrival and departure routes (standard instrument arrival and standard instrument departure) connect some points on C_1 to some other points on C_2. Let $\mathrm{K} \subset \Theta \times \mathrm{I}$ be the subset which contains the pairs of points to be connected on C_1 and C_2.

Given $(i, j) \in \mathrm{K}$, a route connecting points O_i and I_j can be defined as a function $\gamma_{ij} : [0;1] \to R^3$, where $\gamma_{ij}(0)$ represents the starting point and $\gamma_{ij}(1)$ is the ending point.

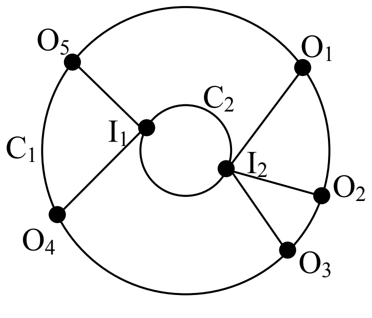

Fig. 1. Example of TMA model

There are two possible situations: route γ_{ij} either starts from an entry point on C_1 and ends at an arrival point on C_2; or it starts from a departing point on C_2 and ends at an exit point on C_1.

This statement can be expressed by the following equations:

$$\left.\begin{array}{l}\gamma_{ij}(0)=O_i\\ \gamma_{ij}(1)=I_j\end{array}\right\} if\, 1\le i\le n_{in}\; and\, 1\le j\le n_{arr}$$

$$\left.\begin{array}{l}\gamma_{ij}(0)=I_i\\ \gamma_{ij}(1)=O_j\end{array}\right\} if\; n_{arr}+1\le j\le n_{arr}+n_{dep} \qquad (1)$$

$$and\; n_{in}+1\le j\le n_{in}+n_{out}$$

We denote the components of γ_{ij} in axis (x,y,z) by $(\gamma_{ijx},\gamma_{ijy},\gamma_{ijz})$ respectively.

The separation minima are expressed as follows, $\forall(i,j),(k,l)\in \mathrm{K},\forall(\mu_1,\mu_2)\in[0;1]$ (it depends on national horizontal and vertical separation criteria):

$$\sqrt{\left[\gamma_{ijx}(\mu_1)-\gamma_{klx}(\mu_2)\right]^2+\left[\gamma_{ijy}(\mu_1)-\gamma_{kly}(\mu_2)\right]^2}\ge H_{s\min}$$
$$\left|\gamma_{ijz}(\mu_1)-\gamma_{klz}(\mu_2)\right|\ge V_{s\min} \qquad (2)$$

We minimize the total distance flown by all the flights during a certain period:

$$L=\sum\nolimits_{(i,j)\in \mathrm{K}} w_{ij}Nl_{ij}\,, \qquad (3)$$

where l_{ij} is the length of route γ_{ij} and w_{ij} is the proportion of flights on route γ_{ij}.

4. Airport and TMA operations optimisation model

The airport and TMA operations optimisation model can be characterized by the technological sequence of operations for every ***departure*** [8]:

- a pushback time (including a gate-holding time);
- a runway assignment and departure fix assignment;
- a route from gate to assigned runway, and then to departure fix;

Also for every ***arrival***:

- a time at arrival fix (which may require a speed control before reaching the fix);
- a runway and gate assignment;
- a route from arrival fix to appropriate runway, and then to gate, with timing.

The elements influencing capacity in the near-terminal area are the gates, taxiways, runways and the airspace in the vicinity of aerodrome.

We consider a time horizon $T=\{1,\ldots,T\}$ of approximately one hour, discretized into small intervals of 20 seconds, being small enough to satisfy requirements of lateral and longitudinal separation minima. We have a set of F flights, with each having a weight class w (heavy, large or small) regarding wake turbulence characteristics and direction of flight O (arrival or departure).

The pair $i=(w,o)$ will be referred to as a flight type, belonging to the set of flight types C (the index i will always refer to a flight type). Flight types are defined in order to calculate the minimum separation time required between two flights on the same runway. There is also a set of runway configurations K. Each configuration k is described by a set of pairs $\{(r_1,m_1),\ldots,(r_N,m_N)\}$, a pair comprising a runway r and a mode of operation m (i.e., arrivals only, departures only, or mixed mode).

Our objective is to minimize a weighted sum of delays:

$$\begin{gathered}\min\Psi=\sum\nolimits_{i\in C}\left(\beta_D^G\big\|_{\{i\in C_D\}}+\beta_A^A\big\|_{\{i\in C_A\}}\right)\sum\nolimits_{r\in R_i}\sum\nolimits_{t\in T}t\psi_{rt}^i-\\ \sum\nolimits_{f\in F}\left(\beta_D^G\big\|_{\{f\in F_D\}}+\beta_A^A\big\|_{\{f\in F_A\}}\right)T_{O(f)}^f+\\ \sum\nolimits_{f\in F}\sum\nolimits_{r\in R_f}\left(\beta_D^A\big\|_{\{f\in F_D\}}+\beta_A^G\big\|_{\{F\in F_A\}}\right)d_r^f\varphi_r^f-(\beta_D^G-\\ \beta_G)\left(\sum\nolimits_{i\in C_D}\sum\nolimits_{r\in R_i}\sum\nolimits_{t\in T}t\psi_{rt}^i-\sum\nolimits_{f\in F_D}\sum\nolimits_{r\in R_f}T_r^f\varphi_r^f\right)+\\ K\sum\nolimits_{t\in T}\chi_t.\end{gathered} \qquad (4)$$

This can be summarized in words as a summation over all flights of the following terms: (weighted time from first time period until touchdown/take-off) – (weighted time from first time period until start time) + (weighted time from touchdown/take-off to destination) – (weighted gate-holding duration) + (configuration change penalty).

We define the following binary decision variables for the model:

- $w_{kt}=\begin{cases}1, if\ config\ k\ is\ active\ at\ time\ t;\\ 0, otherwise;\end{cases}$
- $\varphi_r^f=\begin{cases}1, if\ flight\ f\ is\ assigned\ to\ runway\ r;\\ 0, otherwise;\end{cases}$
- $\varphi_{rt}^i=\begin{cases}1, if\ flight\ of\ type\ i\ arrives\ at\ runway\ r\ at\ time\ t;\\ 0, otherwise;\end{cases}$
- $\chi_t=\begin{cases}1, if\ change\ of\ config\ occurs\ at\ time\ t;\\ 0, otherwise.\end{cases}$

We note that one of the key ideas behind this model and its tractability is that we have chosen to define the variables ψ by flight type, rather than by flight, capitalizing on the fact that separation depends only on flight type, and greatly reducing the number of variables to $O\left(|C||R||T|+|F||R|\right)$, rather than $O\left(|F||R||T|\right)$, and the number of constraints to $O\left(|C|^2|R||T|\right)$, rather than $O\left(|F|^2|R||T|\right)$.

In this model we suppose that the aerodrome taxiway/runway and near-terminal area airspace has infinite capacity. In this case, all flights can fly along their shortest flight tracks without obstruction/separation infringement and hence arrive at their assigned runway within their time-window specified in the input data, and in particular at their assigned time (this can be derived from ψ and φ).

Then, it gives an optimal solution to the airport and TMA operations optimisation model, including the optimal configuration schedule (through ω), the optimal runway assignments (φ), the optimal sequencing of flights (ψ), and implicitly an optimal routing of flights.

5. The TMA queueing analysis uncertainty model

The objective of the uncertainty modelling process is to determine the impact of various uncertainties on the service times (air traffic control and flight operation) in the queuing theory models (Fig. 2) [10,12,13].

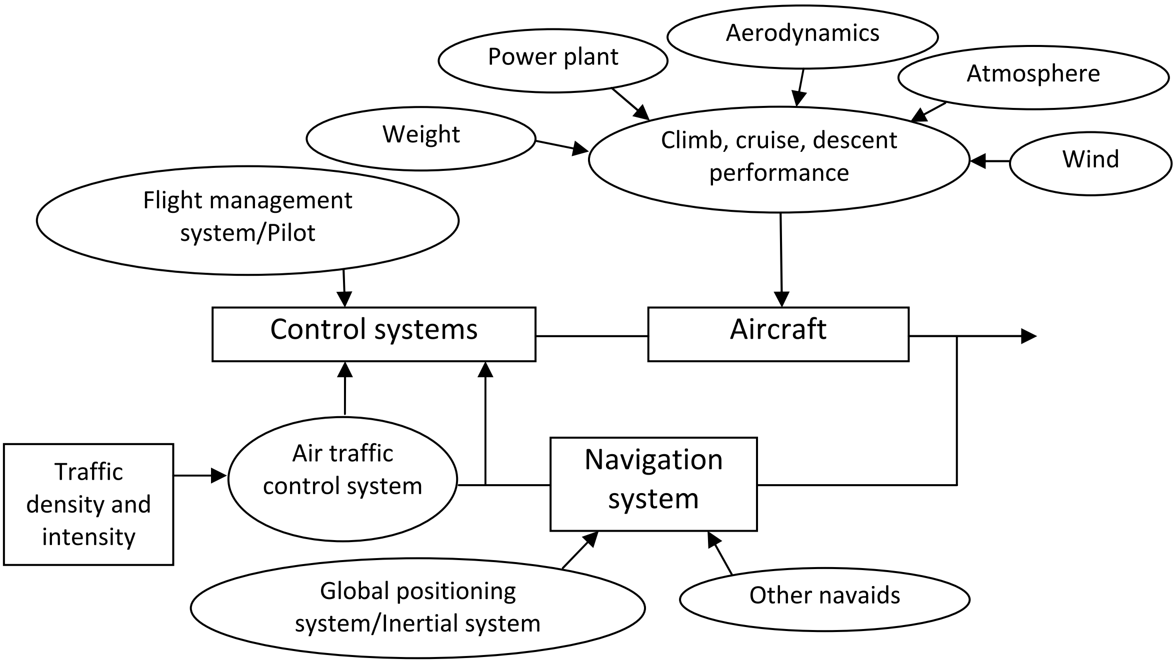

Fig. 2. Aircraft trajectory uncertainties in TMA

Some of these uncertainties influence the climb and descent flight segments, while others affect the cruise segment of flight. Ambient winds, thunderstorm areas, navigation systems and flight plan deviations due to airspace regulations and air traffic management are major contributors to cruise segment of flight uncertainties.

A simplified $l-D$ dynamic model of the aircraft is considered for the uncertainty modelling. This model is represented as a system consisting of the aircraft position x, aircraft speed v and random acceleration n_v [12]:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ n_v \end{bmatrix} \tag{5}$$

The random acceleration term $n_v \sim N\left(0,\sigma_v^2\right)$, is assumed to be white-Gaussian, approximating the uncertainty from the onboard inertial sensor system. The resulting position error is a random process. Periodic position fix inputs are used to correct the drift in the random process. Although very high frequency omnidirectional range/distance measuring equipment (VOR/DME) has traditionally been used for aircraft navigation, the recent trend has been to move towards the use of the Global positioning system (GPS) for obtaining the position fixes. A position fix measurement model can be represented using a measurement model:

$$z = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + n_x \qquad (6)$$

The measurement noise $n_x \sim N\left(0, \sigma_x^2\right)$ is also assumed to be white-Gaussian.

This model can be used to formulate an algebraic Riccati equation that provides the error covariance matrix due to sensor process and sensor noise components as:

$$O = AP + PA^T + Q - PH^T R^{-1} HP \qquad (7)$$

The solution to this equation can then be obtained as:

$$P_{SS} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = \begin{bmatrix} \sqrt{2\sigma_x^3 \sigma_v} & \sigma_x \sigma_v \\ \sigma_x \sigma_v & \sqrt{2\sigma_x \sigma_v^3} \end{bmatrix} \qquad (8)$$

A similar approach might be used to model the uncertainties due to aircraft flight control. The modern commercial aircraft are equipped with the flight management system (FMS) and autopilots. Control inputs commanded by the autopilot are calculated based on the state estimate containing navigational uncertainty errors. Hence, the sensor uncertainty components are fed-back into the system through the feedback control loop, and causes additional output uncertainty.

6. Conclusions

In this work we considered the model for quantitative analyses of air traffic flows in terminal control area, which describes general TMA elements and parameters. Also we analysed the model, which takes into account airport operations jointly with air traffic flows in the vicinity of aerodrome.

Application of such models taking into account uncertainty factors will decrease number of air traffic delays and improve safety of flights in national airspaces. This is also results in increased capacity of terminal control areas, less congestion of the airport surface and near-terminal airspace and reduced fuel costs and associated emissions.

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Моделі кількісної оцінки потоків повітряного руху та пропускної здатності в термінальних диспетчерських районах

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Мета: Метою цієї статті є дослідження прикладних моделей кількісної оцінки потоків повітряного руху та пропускної здатності в термінальних диспетчерських районах в умовах невизначеності. У даній роботі запропоновано теоретичні основи формального опису потоків повітряного руху, що вилітають та прилітають в термінальні диспетчерські райони з метою регулювання пропускної здатності та зменшення затримок польотів в повітряному просторі. **Методи дослідження:** Оптимізація формального опису термінального диспетчерського району, що ґрунтується на моделі, яка складається з типових елементів структури повітряного простору та експлуатаційних процедур, зменшення часу затримок на злітно-посадкових смугах та в повітряному просторі поблизу аеродрому з використанням оптимізаційної моделі операцій на аеродромі та в термінальному диспетчерському районі, оцінка різних типів невизначеності та пов'язаних з цим факторів за допомогою моделі аналізу невизначеностей в термінальних диспетчерських районах методами теорії черг. **Результати:** Формальна модель термінального диспетчерського району, оптимізаційна модель операцій на аеродромі та в термінальному диспетчерському районі та модель аналізу невизначеностей в термінальних диспетчерських районах методами теорії черг. Запропоновано принципи оцінки кількісних характеристик потоків повітряного руху та пропускної здатності в термінальних диспетчерських районах в умовах невизначеності. **Обговорення:** Складові елементи формальної моделі термінального диспетчерського району, принципи зменшення затримок в результаті застосування оптимізаційної моделі операцій на аеродромі та в термінальному диспетчерському районі та оцінка впливу факторів невизначеності на обслуговування повітряного руху та виконання польотів за допомогою моделі аналізу невизначеностей в термінальних диспетчерських районах методами теорії черг.

Ключові слова: аеронавігаційна система; безпека польотів; моделі потоків повітряного руху; обслуговування повітряного руху; управління потоками повітряного руху та пропускною здатністю; фактори невизначеності; формальна модель термінального диспетчерського району.

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Модели количественной оценки потоков воздушного движения и пропускной способности в терминальных диспетчерских районах

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Цель: Целью данной статьи является исследование прикладных моделей количественной оценки потоков воздушного движения и пропускной способности в терминальных диспетчерских районах в условиях неопределенности. В данной работе предложены теоретические основы формального описания потоков воздушного движения, вылетающих и прилетающих в терминальные диспетчерские районы с целью регулирования пропускной способности и уменьшения задержек полетов в воздушном пространстве. **Методы исследования:** Оптимизация формального описания терминального диспетчерского района, основанная на модели, которая состоит из типовых элементов структуры воздушного пространства и эксплуатационных процедур, уменьшение времени задержек на взлетно-посадочных полосах и в воздушном пространстве вблизи аэродрома с использованием оптимизационной модели операций на аэродроме и в терминальном диспетчерском районе, оценка различных типов неопределенности и связанных с этим факторов с помощью модели анализа неопределенностей в терминальных диспетчерских районах методами теории очередей. **Результаты:** Формальная модель терминального диспетчерского района, оптимизационная модель операций на аэродроме и в терминальном диспетчерском районе и модель анализа неопределенностей в терминальных диспетчерских районах методами теории очередей. Предложены принципы оценки количественных характеристик потоков воздушного движения и пропускной способности в терминальных диспетчерских районах в условиях неопределенности. **Обсуждение:** Составляющие элементы формальной модели терминального диспетчерского района, принципы уменьшения задержек в результате применения оптимизационной модели операций на аэродроме и в терминальном диспетчерском районе и оценка влияния факторов неопределенности на обслуживание воздушного движения и выполнения полетов с помощью модели анализа неопределенностей в терминальных диспетчерских районах методами теории очередей.

Ключевые слова: аэронавигационная система; безопасность полетов; модели потоков воздушного движения; обслуживание воздушного движения; управление потоками воздушного движения и пропускной способностью; формальная модель терминального диспетчерского района; факторы неопределенности.

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