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Trajectory Optimization for vertical navigation using the Harmony Search algorithm

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Abstract: Global warming has become a major concern, and several solutions have been proposed to reduce CO2 emissions. Aircraft are responsible of 2% of the global carbon dioxide (CO2) emissions, and the aerospace industry has committed to reduce by 2050 its carbon footprint to 50% of the emissions recorded in 2005. Among the many studies to achieve this goal, flight trajectory optimization seems to be a very promising solution. The main objective of this paper is to propose an optimization algorithm based on the Harmony Search algorithm to optimize the vertical profile (VNAV) of a flight (climb and cruise) without step climb to reduce fuel consumption. The algorithm was developed in Matlab and results compared to an exhaustive search which computes all the possible candidates and finds the optimal one. It has been tested on a commercial plane for three destinations and three different weights.

Keywords: Optimization, Fuel, Vertical Navigation, Harmony Search, Exhaustive Search,

1. INTRODUCTION

Among the various means of transport, it is air transportation that is expanding the most for the past few decades, and it is also one of the most popular with occupancy at 78% in 2011 (ATAG, (2013)). Every day, there are 8.6 million passengers and 99,700 flights(ATAG, (2014)). Aviation is the fastest way to get from one point of the globe to another, which gives it a huge advantage over other means of transport for business and for tourism (ATAG, (2014)). It is thus imperative that the aviation industry continues its efforts to reduce fuel consumption; for a healthier environment and to manage (and reduce) cost, by improving aircraft materials and engines as well as optimizing flight trajectories.

Global warming has been changing the planet's environment and has become one of the major concerns of the 21st century. Airline operations produced and released 689 million tonnes of carbon dioxide (CO2) in 2012 and 705 million tonnes in 2013 (ATAG, (2014)). According to the Air Transport Action Group (ATAG), aircraft produced around 2% of the global carbon dioxide (CO2) emissions (ATAG, (2011)). Even though 2% is rather low it still represents a significant percentage that the industry needs to address, especially given the expected increase in air traffic.

The aerospace industry is aware of aviation's environmental impact, and has set itself several targets, such as improving its fleet's fuel efficiency by 1.5% per annum until 2020, and reducing the net aviation carbon emissions by 50% by 2050 (ATAG, (2013)). Some of the ways to achieve these goals include engine improvements (Salvat et al., 2013) and the use of biofuels. Flight tests on several aircraft have indicated that biofuels are a very promising alternative (IATA, 2009). Observations and tests have revealed that a reduction of 20% in airplane drag will lead to an 18% reduction in fuel consumption(Okamot et al., 2005). These examples are only a small sampling of the efforts being made to reduce fuel consumption. However, even though they are promising, their implementation can be very complicated.

Some other solutions which are much easier to put into practice have been proposed, such as aircraft trajectory optimisation, which gives very good results. We can optimise two types of trajectories: VNAV (Vertical navigation) and LNAV (Lateral Navigation), in this paper we consider only VNAV, in which speed and altitude are optimised. The flight management system (FMS), which was developed in 1970's and implemented in the 1980's (Lidén, 1994), is a box in the cockpit that provides a flight plan to the pilot. The input data is recorded in the FMS, which indicate to the pilot the route, speed and altitudes to follow in order to consume the least amount of fuel and thus reduce the cost.

Lidén was the first researcher to work on flight trajectory calculation with FMS's (Lidén, 1985). He sought to minimize flight cost using speed control and attempted to estimate the Cost Index (CI) with FMSs.

To define the optimal trajectory and estimate the cost, an FMS needs a mathematical model. To describe the behaviour of an aircraft, we use Equations of Motion (EoM), which is a nonlinear equation (Ghazi and Botez, 2015, Ghazi, 2014). However, in case of FMSs, their limited processing capacity prevents them from utilising EoM; instead, the FMS needs tables with experimental data in order to provide results. (Hagelauer and Mora-Camino, 1998) showed that the FMS requires this data instead of the equations of motion.

Murieta-Mendoza developed a method to calculate a VNAV trajectory cost for a total flight (climb, cruise, and descent) a

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performance database for two aircraft (Murrieta-Mendoza and Botez, (2014)-a) and also developed an algorithm to calculate the optimal VNAV profile and reduce the search space (Murrieta-Mendoza and Botez, (2014)-b). Dancila et al. estimated the fuel burn for cruise divided into several segments at constant altitude using experimental data (Dancila and Botez, (2011), Dancila et al., (2013)). Félix Patron et al. used a genetic algorithm to optimize trajectories under the influence of wind (Félix Patron et al., 2013) and studied how to couple vertical and lateral profiles to optimize a trajectory through genetic algorithms (Félix Patron and Botez, 2014).

The main objective of this paper is to develop a meta-heuristic algorithm to optimize a flight trajectory including climb and cruise without step climb which represents change of altitude in cruise regime. This algorithm is based on the premise that music will seek to find the perfect harmony. The Harmony Search algorithm has shown very promising results in other domains (Geem and Hwangbo, 2006, Erdal and Saka, (2006), Degertekin, 2008) and so we are working to implement it in flight optimization. It uses numerical data and has been compared to an exhaustive research algorithm. The exhaustive research provide us the global optimum hence the interest to compare it with the Harmony Search algorithm.

This paper is organized as follows: A conventional flight and a method to calculate its global flight cost is defined to provide some background. Next, we introduce the Harmony Search algorithm and explain how it works. The results of the harmony search algorithm are then presented along with conclusion and proposed future works.

1 METHODOLOGY

1.1 Complete Flight Phases

Figure 1 shows a conventional commercial flight: Initial climb begins at 2000ft with a constant speed equal to an Indicated Airspeed (IAS) of 250kts until an acceleration phase due to start after 10,000ft until the desired constant climb speed. During the climb, the Airspeed Indicator (ASI) leads off at the IAS to Mach when the plane passes through the crossover altitude. At this point, the plane's reference speed is Mach. This speed reference will be preserved throughout the cruise, which begins from the Top of Climb (TOC) to the Top of Descent (TOD), until the plane returns to the crossover altitude on the descent. During cruise, step climbs (change of altitude) can be considered in order to improve fuel consumption. In this paper the cruise has been done with one constant altitude and one constant speed. The descent is calculated in the same way as the climb. As we have not considered the descent in this paper, it will not be detailed.

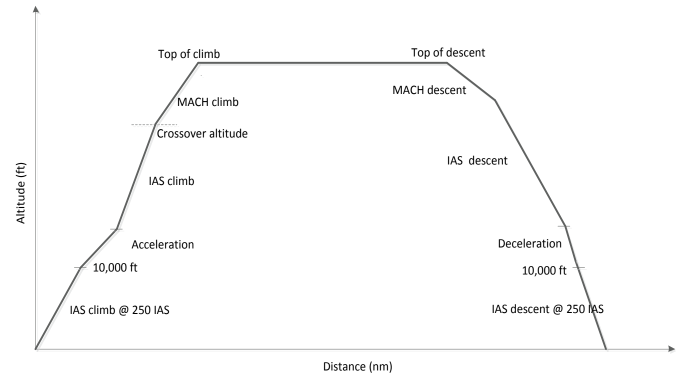

Figure 1: Conventional Flight

1.2 Global Flight Cost

The global flight cost is defined as:

$$Cost = Fuel\ Burned + CI * Flight\ Time \qquad (1)$$

where Fuel Burned represents the total fuel burned during flight (Kg), Flight Time represents the total time of the flight (hr) and CI is the Cost Index, given in Kg/hr.

"The CI is the ratio of time-related cost of an airplane operation and the cost of fuel. The value of the CI reflects the relative effects of fuel cost on overall trip cost as compared to time-related direct operating cost" (Roberson, 2007). A higher CI neglects the cost of fuel and gives priority to a faster flight, while a CI equal to 0 means that reduction of fuel consumption is a priority over flight time. In this paper, we consider CI equal to 0.

1.3 The performance Database

The performance model gives us the information required to compute the fuel burned. The database is a numerical model of an aircraft given by its manufacturer, based on flight tests. It is divided into seven sub-databases.

To respect Air Traffic Management (ATM) flight constraints we consider an altitude-step of 1,000 ft between each point of climb and cruise. The altitudes are thus automatically taken from the database and are well-known. For speed we used the existing values of the database given by our industrial partner. Moreover, some parameters such as weight and International Standard Atmosphere (ISA) deviation temperature change throughout the flight and we cannot control or change these. This is why an interpolation is required when ISA deviation temperature and weight are not available in the database. The general interpolation schema is shown in figure 2 for "climb IAS"; it should be observed that for each flight phase, the figure interpolation changes. The cruise is divided into several separate segment of 25nm between each waypoint. An interpolation is made each 25nm. The word « limit » means the value taken from the Performance Data Base (PDB) which frames the value to interpolate.