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Effects of linear holding for reducing additional flight delays without extra fuel consumption

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an approach to implement linear holding (LH) for flights initially subject to ground holding, in the context of Trajectory Based Operations. The aim is to neutralize additional delays raised from the lack of coordination between various traffic management initiatives (TMIs) and without incurring extra fuel consumption. Firstly, motivated from previous works on the features of LH to absorb delays airborne, a potential applicability of LH to compensate part of the fixed ground holding is proposed. Then, the dynamic adjustment of LH in response to TMIs-associated tactical delays is formulated as a multi-stage aircraft trajectory optimization problem, addressing both pre- and post-departure additional delays. Results suggest that additional delays of 25 mins in a typical case study can be totally recovered at no extra fuel cost. A notable extent of delay reduction observed from the computational experiments further supports the benefits of LH for reducing different combinations of additional delays without consuming extra fuel.

1. Introduction

In the recent 16th ATIO (AIAA) conference, Bilimoria (2016) presented an analysis of the additional delays experienced by flights subject to ground holding for Ground Delay Programs (GDPs) or Airspace Flow Programs (AFPs). Statistic results obtained from five airports of arrivals suffering the most pre-departure ground holding in 2015 were shown, suggesting that the additional delays of those EDCT (Expect Departure Clearance Time) affected flights were substantially larger in four of the five airports (about two to three times on average) than for arrivals that were not subject to ground holding. At the same conference, a similar analysis of "double delay" (or "double penalty"), due to the interaction between GDPs and arrival metering (terminal scheduling delays), was presented by Evans and Lee (2016), providing a deep dive into the underlying causes of those double delays and the circumstances in which they occur in real operations.

Imagine a flight held on ground due to a GDP/AFP, before being rerouted around a thunderstorm, and then subject to the Miles-in-Trail (MIT) as it passes through a congested sector, as described in Dwyer et al. (2011). The joint impact of all these initiatives together, however, may not be well coordinated and eventual inequities in their implementation may be perceived for the airspace user. Under current operations, delays assigned by the GDP/AFP are normally transferred from the area of affected capacity to the departure airport, while imposed entirely on the EDCT, prior to take-off. As a consequence, it is possible that some unnecessary delays may have been performed through the ground holding, before the controlled flight encounters other initiatives yielding delays likewise, which again pushes back its final arrival time.

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The above discussions might point to a drawback of ground holding: its low flexibility, especially in terms of integrating among various Traffic Management Initiatives (TMIs), as reported by Grabbe et al. (2011) and Rebollo and Brinton (2015), being a real problem in the United States National Airspace System (NAS). Even so, ground holding is still preferred nowadays to absorb delays because less fuel consumption is incurred if compared with typical airborne holding. In order to overcome some of the ground holding drawbacks, Delgado et al. (2013), Delgado and Prats (2013, 2014) proposed a cruise speed reduction strategy aimed at partially absorbing delays airborne, where ground delayed flights were allowed to cruise at the lowest possible speed in such a way the specific range remained the same. In this situation, the fuel consumption kept unchanged while some linear holding (LH) was performed in compensation with the reduced ground holding. Concretely, differentiating from typical airborne holding, which would consume more fuel due to the extended flight track (such as vectoring or using holding patterns), this LH is also performed airborne but done progressively by flying slower along the original planned route whilst having no extra fuel consumed than initially scheduled.

As the core method to perform LH, speed reduction is one of the speed control strategies that have proven effective for several Air Traffic Management (ATM) scenarios. For instance, Jones et al. (2013, 2015) presented a speed control approach for transferring delay away from the terminal to the en route phase, from which significant fuel saving on a per flight basis was yielded, and the performance of GDP was reported improved through a dynamic speed adjustment mechanism. In Günther and Fricke (2006), a pre-tactical speed control was applied to prevent aircraft from performing holding patterns when arriving at a congested airspace, improving both flight efficiency and controller workload level. More widespread applications for conflict management have been under research for decades (Tomlin et al., 1998), where the speed control strategy was used, in addition to other effective manners such as path stretching or flight level adjustment for instance.

More recently, the LH strategy was further extended by the same authors of this paper in Xu et al. (2016), where, through using trajectory optimization techniques, the whole flight profile including climb, cruise and descent phases were subject of realizing LH, being a remarkable increase appreciated in terms of the maximum amount of airborne delay that can be generated without extra fuel consumption. Yet, as a primary study in this regard done by the authors, reference (Xu et al., 2016) mainly focused on the inclusion of climb/descent flight phases into the LH strategy, without paying any attention on the discussions of the subsequent applicability (e.g., a delay recovery process) and the effects on potential fuel savings. This paper, as a result, is devoted to take advantage of the former research and complement the side of potential applications.

With the paradigm shift proposed by NextGen and SESAR programs, evolving from an airspace-based ATM to Trajectory Based Operations (TBO), the proposed LH could be expected to provide a high flexibility with regard to the cost-based delay management. The purpose of this paper is to implement LH to substitute part of the ground holding, adjusted dynamically in response to potential TMIs that might produce tactical delays during pre- and post-departure phases. In such a way, our aim is to reduce the additional delays as much as possible at no extra fuel cost. For this purpose, an optimal trajectory generation technique is used to formulate each of the steps of the implementation, followed by a case study illustrating in detail the effects of dynamic adjustment of LH to a specific flight, as well as computational experiments on the capability of delay recovery with respect to different TMIs-associated delay combinations.

2. Motivation

Fig. 1 illustrates some key flight-related events (blue rectangles) and respective time intervals. In Bilimoria (2016), historical flight operations from five airports (LGA, SFO, EWR, JFK, PHL), whose arrivals experienced the most pre-departure ground holding in 2015, were examined computing the variance between scheduled times and actual times. According to this study, each of the flight-related events of Fig. 1 can be associated with a possible additional delay event (red[1] rectangles in the figure).

Consider a particular flight affected by a GDP (or an AFP, where the affected area is not at the destination airport but somewhere en-route). To be more precise, a GDP is usually implemented at airports where capacity has been reduced because of weather (such as low ceilings, thunderstorms or wind) or when demand exceeds capacity for a sustained period. The FAA (Federal Aviation Administration) assigns arrival "slots" to aircraft based on the available capacity and flight arrival times, and adds delay in sequential order until demand equals capacity. This process affects all flights within the defined "scope" (i.e., which flights are captured) of the program, which in turn can be specified by distance, by tier, or by time. For more details about the procedure, the readers may refer to FAA (2009). Nevertheless, it should be noted that the application of the proposed strategy should not be limited for GDP only. We choose the GDP as an illustrative example, as it is nowadays widely used in real practice.

As mentioned above, because of the capacity reduction at the destination airport, the arrival time becomes "controlled" and postponed by a certain GDP delay (from "Scheduled Flight" to "Scheduled Flight in GDP" in Fig. 1). At present, time-of-arrival control is not enforced and a time-of-departure control is preferred. The reason is because a departure time is actually enforceable, being much more difficult to enforce the arrival time with current navigation and guidance technology. Thus, the assigned delay is entirely transferred from the arrival airport to the departure in the form of ground holding (GH) also to avoid (relatively) costly airborne holding, and to obtain a parallel shift on the scheduled arrival time (Wheels On in the figure).

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[1] For interpretation of color in Figs. 1 and 3, the reader is referred to the web version of this article.