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Investigating string stability of a time-history control law for Interval Management

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ABSTRACT

Interval Management (IM) is a concept being developed as a part of the Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR). The objective of Interval Management is to achieve a more precise spacing interval between an IM aircraft and an assigned target aircraft. Speed commands, calculated by avionics onboard the IM aircraft using state information from the target aircraft received by ADS-B, are implemented by the IM aircraft in order to achieve a desired spacing interval relative to its target aircraft. In some IM operations, it is expected that a string of IM aircraft will be formed, where each aircraft is spacing relative to its immediately preceding aircraft. In the design of a speed control law that calculates speed commands for the IM aircraft, one must not only examine the performance and stability of one aircraft relative to another, but also the performance and stability of the entire string. String behavior fundamentally affects the potential operational practicality of successfully implementing Interval Management in certain environments. This paper presents a simplified, closed-form string stability analysis for a time-history speed control law, which has been proposed for Interval Management. Simulation results are shown to validate the closed-form analysis and are used to evaluate string behavior and system performance for an approach-spacing operation.

1. Introduction

Interval Management (IM) is a concept being developed jointly by US and European organizations to support the goals and objectives of the Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR), respectively. In the US, the FAA's Surveillance and Broadcast Services (SBS) office is sponsoring a significant effort to develop IM. The advent of ADS-B technology is leading to the development of cockpit-based avionics that take advantage of the increased situational awareness available to the flight crew. IM is one of a number of efficiency- and safety-enhancing concepts that are enabled by ADS-B. The goal of IM is to achieve precise inter-aircraft spacing as a means to increase the efficiency of a variety of operations. In IM operations, avionics provide the flight crew of the IM aircraft with speed commands that will achieve and maintain a desired spacing interval relative to a target aircraft. Approach spacing is being considered as an initial application of IM, where the operational goal is to increase the arrival throughput of busy airports by more precisely spacing aircraft at the final approach fix (FAF) or runway threshold. In addition, IM is expected to reduce controller workload.

Previous research has demonstrated the benefits of delegating spacing (or separation) responsibility to the flight crew during approach operations in order to achieve more precise inter-aircraft spacing and to reduce controller workload. Researchers have investigated using a cockpit display of traffic information (CDTI) to display relevant traffic information to the flight crew that enables self-separation without controller intervention (Sorensen and Goka, 1983; Pritchett and

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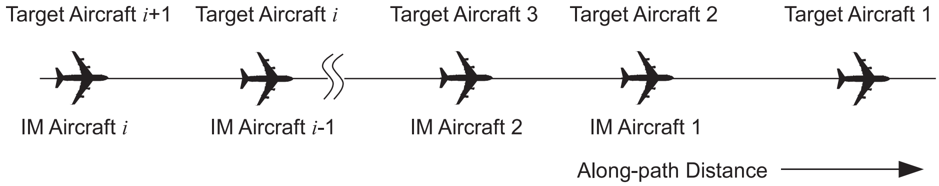

Fig. 1. Depiction of a string of aircraft performing an IM operation.

Yankosky, 2000). In addition, the large variations in low-noise and fuel-efficient approach trajectories have led to research into pilot tools and procedures that allow the more efficient trajectories without sacrificing capacity (Ren et al., 2003; Prins et al., 2005; de Gaay Fortman et al., 2007). Prins et al. (2005) and de Gaay Fortman et al. (2007), in particular, present a flap-scheduling tool designed to aid the flight crew in maintaining separation on approach and achieving a required time of arrival (RTA) at the runway, respectively.

In contrast to the previously mentioned research, IM aircraft will have onboard avionics that determine the speeds needed to achieve and maintain a desired spacing interval relative to a target aircraft. The avionics, referred to as the IM equipment, will use a speed control law to calculate the speed commands that are needed, where commanded speeds are a function of the state information transmitted by ADS-B from the target aircraft. Researchers at NASA Langley Research Center have developed a speed control law for terminal area spacing, which determines speed commands that are a function of the difference in the IM and target aircraft estimated times of arrival (ETAs) at the runway threshold (Barmore, 2006; Krishnamurthy et al., 2005; Abbott, 2002; Barmore et al., 2008). This is a trajectory-based speed control law, which assumes some knowledge of the planned arrival trajectories for the IM and target aircraft in order to calculate their respective ETAs. One advantage of NASA's trajectory-based control law is that aircraft on different routes can still be spaced precisely at the runway threshold. EUROCONTROL has developed and analyzed a time-history control law, sometimes referred to as a constant-time-delay control law, for spacing aircraft directly to a merge point after which the aircraft are on a common route. The time-history control law is designed to minimize the longitudinal, or along-path, distance between the IM aircraft's current position and the target aircraft's position τ seconds in the past, where τ is the desired (time-based) spacing interval (ASAS, 2006; Hoffman et al., 2003; Ivanescu et al., 2006). The primary advantage of EUROCONTROL's time-history control law is that information about the planned trajectories of the IM and target aircraft is not required. Both of these speed control laws have had extensive performance testing in simulation environments. Additionally, a variant of EUROCONTROL's time-history control law has been implemented and flight tested by UPS (Barmore et al., 2009).

The IM aircraft's objective in an approach-spacing operation is to achieve and maintain a desired (time-based) spacing interval relative to the target aircraft. Time-based spacing is defined as the difference in the target and IM aircraft's times over a common point. For example, given a 90-s desired spacing interval, the IM aircraft should cross a common point 90 s after the target aircraft crossed that same point. Because aircraft are descending and decelerating on the approach to the runway, distance-based spacing would not be practical (i.e., to maintain a constant distance relative to the target aircraft, the IM aircraft would need to match the target aircraft's speeds). A time-based spacing interval allows for the distance compression that naturally occurs between aircraft when the target aircraft slows down before the IM aircraft. Thus, a speed control law for the approach-spacing application must enable the IM aircraft to achieve and maintain a desired (time-based) spacing interval without matching the target aircraft's speeds.

In approach-spacing IM operations, it is expected that a string of IM aircraft will be formed, where each aircraft implements speed changes in order to achieve the desired spacing interval relative to its immediately preceding target aircraft. Fig. 1 depicts a string of aircraft performing an IM operation. String stability describes how spacing errors are propagated through a string as a result of changes in target aircraft speeds.[1] In the design of a speed control law for IM, string stability of the selected speed control law must be considered. With a goal of developing IM equipment for near-term national airspace system (NAS) improvements, a greater understanding of string stability analysis and its implications for actual IM operations is needed.

The objective of this paper is to present the string stability analysis for a time-history control law, which has already been implemented and flight tested in first-generation IM equipment. Closed-form analysis for the string stability of a time-history control law is derived assuming a simplified aircraft model. Results from this analysis are then related to well known results from the string stability literature. String stability results for a modified time-history control law, previously shown to improve string behavior, and for variations in aircraft performance and control gains are also presented. The closed-form analysis is intended to provide insight into the string behavior for the time-history control law and is the main contribution of the paper. Simulation results for a nonlinear aircraft model are used to validate the closed-form analysis and to relate that analysis to a realistic IM operation. Other techniques for improving string behavior are explored using the simulation environment.

[1] It should be noted that string stability describes the overall behavior of the aircraft string and is not related to stability of an individual aircraft and its ability to be controlled to desired states.