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Effects of flare operation on landing safety: A study based on ANOVA of real flight data

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A B S T R A C T

Final approach and landing are generally defined as the two riskiest stages of flight due to their much higher accident rates than other phases. Long landings and hard landings are two kinds of abnormal events frequently occurring during the landing phase and also significantly increase the risk of landing accidents. The aim of this study was to examine the effects of pilot's critical flare operation on long and hard landing events based on real flight Quick Access Recorder (QAR) data. 293 flight QAR data samples were collected from airlines and 21 flight parameters from each sample were selected and calculated by programing. Then, an analysis of variance was carried out for finding flight parameter characteristics of abnormal landing at a flare initial point and in the whole flare process. Lastly, two regression models were developed to analyze the potential correlations between flare operations and landing performance. The study found that flare operation would greatly influence touchdown distance and touchdown vertical acceleration, the control column and throttle operation in flare would affect landing performance conjointly and pilots' quick and steady pulling up of the columns and softer throttle reduction are helpful for a better flare performance. These findings could be the basis of developing a mathematical and quantitative model for further revealing the relationships between pilot operations and landing performance, which can also be applied in practice to prevent landing incidents and even accidents.

1. Introduction

Pilots' operation performance can affect flight safety directly (Reason, 1990; Ebbatson et al., 2010). Many studies have reported that pilot error is the primary cause of over 60% of flight accidents (Shappell and Wiegmann, 1996; Shappell et al., 2007; Jarvis and Harris, 2010). The statistics on commercial flight accidents in China from 2007 to 2016 indicated that flight crew factors contributed to 63.64% of accidents (Civil Aviation Administration of China, 2017). Particularly in the final approach and landing stage, the occurrence rate of pilot error is significantly higher than other phases because pilots need to deal with more situational change, greater decision-making and higher operational activity (Wickens and Hollands, 2000; Stanton et al., 2009; Rosa et al., 2011). Statistics released by Boeing have also indicated that landing phase alone accounted for 24% of total fatal accidents occurring from 2007 to 2016, despite the fact that the landing phase accounts for just 1% of average flight time (Boeing, 2017). Long landings and hard landings are two kinds of abnormal events frequently occurring during the landing phase. A long landing is defined as when an aircraft's touchdown distance on runway exceeds the standard area and a hard landing is when the touchdown vertical load exceeds limited value (The standard values are generally regulated by air carriers and aviation administrators). These two kinds of abnormal events remarkably increase the probability of aircraft damage and even flight accidents such as Runway Excursions (RE) and Controlled Flight Into Terrain (CFIT) (Wang et al., 2014).

Currently, most commercial aircraft have been equipped with an advanced autopilot system and automatic Instrument Landing System (ILS). These systems have great effects in most of cruise and gliding stage, especially if there is a low Runway Visual Range (RVR), but they are not fully utilized in common visual landing operation of flight below 60 m (Suzuki et al., 2006) because pilots often take over aircrafts after visually finding a runway and passing the Decision Height (DH) point. In fact, the final visual landing is generally finished by human control, and pilots are required to change the aircraft attitude in a few seconds for a safe and smooth landing. This is achieved by performing the landing flare operation, which involves lifting of the nose to both land the aircraft on the main gear first and decrease the descent rate and vertical load at touchdown. If performed correctly, the flare maneuver would reduce the aircraft's descent rate to acceptable levels so

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that it settles gently on the main landing gear (Grosz et al., 1995; Benbassat et al., 2002). However, the landing flare operation is considered one of the most technically demanding aspects of piloting. Both novice and expert pilots consistently rate the landing flare as one of the most difficult flight maneuvers (Benbassat et al., 2002; Ebbatson et al., 2008). It has been conservatively estimated that 18% of all landing accidents in the U.S. between 1995 and 1998 were due to problems with the landing flare (Benbassat et al., 2002, 2005). It can be seen that flare operation is related with landing performance and safety closely.

In the field of landing safety, previous studies more specifically focused on accidents such as runway overruns and excursions. Kirland et al. (2004) found that 20% of the overruns touched down more than 850 m from the threshold compared with none of the normal flight sample. Rosa et al. (2011) proposed a series of probabilistic models to estimate accident risk (due to runway overrun and landing undershoot). Multiple factors related to environments such as wind, runway surface conditions and runway distance available were involved in these models and studies (Khatwa and Helmreich, 1999; Kirland et al., 2003), but pilot's operation has seldom been mentioned. Some other studies (Grosslight et al., 1978; Wewerinke, 1980; Galanis et al., 2001) addressed the effect of visual perception on pilot's manual operation in landing. Grosslight et al. (1978) found that those landings with monocular approaches tended to be longer and harder. Galanis et al. (2001) also pointed out that changes in the aspect ratio of the runway would affect the perceived glide-slope. Palmisano and Gillam (2005) examined the accuracy of visual touchdown point perception during oblique descents (1.5–15°) through experiments in simulators, the results showed that optic flow per se did not appear to be sufficient for a pilot to land an airplane. Both Mori et al. (2007) and Jorg and Suzuki (2010) used simulator experiments to analyze visual cues and human-pilot control inputs during the landing phase. Their research results showed that the change of the apparent angle between the runway edges was identified as the main cue for flare timing. Meanwhile, the importance of flare operation was also addressed (Mori and Suzuki, 2010).

In fact, fewer studies paid attention to the crucial flare operation in landing. Benbassat et al. (2002, 2005) examined flare operation and depth perception based on 6676 aircraft accident reports and a 21-item perception questionnaire. Results revealed that pilots believed the flare to be more difficult than nine other standard flight maneuvers and most of them used visual cues to time the initiation of flare. Results also showed that experience and instruction were the most important factors for proper flares. Mulder et al. (2000) implemented an experiment to study the effects of pictorial detail on the timing of landing flare where results indicated that landing performance is improved when ground texture is added to the display. Palmisano et al. (2008) also examined three visual strategies for timing the initiation of the landing flare and demonstrated a significant effect of flight experience on flare timing accuracy. Wang et al. (2014) applied a new method for landing safety research by using real flight QAR data to analyze performance features of long landing incidents, the results indicated that significant differences of flight performance existed in the flare phase between normal landing and long landing. In summary, current research consistently demonstrated the importance of flare operation and most has tried to discover factors leading to a perfect flare in a qualitative way. At present, the outcome with regards to flare based on real flight data has rarely been found.

The aim of this study was to examine the effects of pilots' flare operation on landing incidents based on real flight Quick Access Recorder (QAR) data, especially its influences on landing touchdown distance and touchdown vertical load, which are two parameters judging long landing and hard landing.

2. Methods

2.1. QAR data processing

The QAR is a system that can acquire aircraft operational data easily. It includes airborne equipment for recording data and a ground software station for storing and analyzing data. A QAR record all kinds of aircraft parameters, pilot operation parameters, environmental features, and alarm information during a whole flight. The QAR data sampling frequency can reach as high as 16 Hz in modern aircraft. Based on related operational rules and regulations, commercial airlines always use flight data (such as QAR data) to monitor and analyze the whole aircraft and pilot operation performance in flight. When there is a flight parameter that exceeded the prescriptive normal range, it is called a QAR Exceedance Event. In most of time, exceedance events would not lead to severe results, but they can increase the probability of an accident and bring potential damages to aircraft and even passengers. Long landing and hard landing are two kinds of most frequent happened exceedance events, which were classified as abnormal landing events in this study.

QAR data used in this study were collected from three Boeing 737–800 aircrafts operated by local commercial airlines of Tianjin. 293 flights with visual landing operation in daytime and less influence of weather were selected out as samples in this study. The basic selecting principles of samples are described as follows: The man operation or auto operation was checked by switch variable 'auto pilot (A/P)' in QAR recorded data. The meteorological conditions were also considered when selecting samples. First, the data of wind speed and wind direction below 200 feet of each sample flight were calculated for verifying if there was wind shear or turbulence present. Moreover, the threshold of wind speed for choosing sample flight was 10 m/s. Second, those flights with severe landing weather conditions such as storm were not entered in sample group. Third, the landing airports for all flight samples were Category 4E and 4F which means the length of runways were greater than 1800 m. Fourth, those flights with landing at high-altitude aerodromes were excluded and the gross weight of sample flights was also considered. Finally, 293 flight samples were selected and their QAR data were processed. Each original data sample was a CSV (Comma Separated Value) file with thousands of rows and columns. Because it is time-consuming to deal with these unprocessed data manually, a program based on VBA (Visual Basic for Applications) was written and applied to minimize file volume and mine target information from massive QAR data.

2.2. Flight parameter selection

An aircraft in flight is affected by many factors such as external atmospheric environments, the aircraft itself, pilots' basic capabilities and skills, pilots' mental state, and so on. Regardless of how these factors change, however, their effects ultimately are reflected in the change of aircraft attitude and kinematic parameters (Fang, 2005; Chen, 2007). General kinematic analysis of flight is shown in Fig. 1.

In final landing stage, aircrafts always fly within the profile of a landing glide path; their position changes in lateral axis are limited. The aim of landing is to let the aircraft touchdown with a proper groundspeed, sink rate, vertical load, and attitude. Meanwhile, the flare operation directly causes the change of pitch angle. Therefore, we focused on analyzing longitudinal and vertical parameters in this study. Finally, 19 columns of relevant original QAR data of each file were refined. Then 21 flight parameter variables were selected and calculated as shown in Table 1 based on VBA programs. These parameter variables cover all flight and operational parameters in the critical visual and manual landing stages from flare initial height to touchdown point.

The flare initial point in this study is higher than standard 30 feet indicated in most flight operation manuals. This is because any slight backward pulling of the control column could be recorded by a Quick Access Recorder, causing that the time and height of flare are earlier than the theoretical value. The variables of *Touchdown Distance* and *Vertical Acceleration* at touchdown point are two parameters used to determine a long landing and hard landing, respectively. The flare and touchdown process is as shown in Fig. 2. The *Touchdown Distance* is defined as the horizontal distance from the radio altitude of 50 feet to