An Analysis of Hard Landing Incidents Based on Flight QAR Data

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Abstract. Hard landing is one kind of typical landing incidents that can cause passenger discomfort, aircraft damage and even loss of life. This paper aimed to find out flight performance and operation features of hard landing incidents by using the methods of variance analysis, regression modeling and flare operation analysis based on flight QAR data. Results showed that pilots need to control the aircraft to an appropriate groundspeed and descent rate before descending to the flare initial point. Then control column and throttle operation in flare maneuver would affect landing performance conjointly. The logistic model showed that the vertical load of touching ground was actually linked with touchdown attitude and configuration closely, including three variables of pitch angle, roll angle and flap degree. These findings were expected to be applied in practice to prevent hard landing incidents and even landing accidents.

Keywords: Hard landing, QAR, flight safety, flare.

1 Introduction

Final approach and landing is the most important flight phase because a pilot needs to deal with more operations, decision-making, and workloads than other phases [1-4]. Hard landing is one kind of typical landing incidents which is defined as the main landing gear impacts the ground with a greater vertical speed and force than in a normal landing. Hard landings can vary in seriousness from simply causing mild passenger discomfort to situations resulting in serious vehicle damage, structural failure, and even loss of life [5-7]. When an aircraft has experienced a hard landing it has to be checked for damage before its next flight. Statistics also showed that hard landings happened frequently.

Though many studies regarding hard landing have been conducted, most of them have been based on models or experiments rather than real flight data [8-10]. Quick Access Recorder (QAR) is an airborne system which can record all kinds of position parameters, movement parameters, operation and control parameters, and alarm

D. Harris (Ed.): EPCE 2014, LNAI 8532, pp. 398–406, 2014.

information in the whole flight phase. The hard landing was judged by the parameter of vertical acceleration. It is generally monitored by using QAR data in most commercial air carriers, but these data are also confidential for them. Meanwhile, there are few aviation administrators whom enforced their airlines to install QAR equipment on every commercial transport jet [13]. Therefore, QAR data were difficult and rarely utilized into research. This paper aims to find out flight performance and operation features of hard landing incidents through analyzing QAR data and put forward the prevention measures at the same time.

2 Methods

2.1 QAR Data Collection and Processing

The 119 cases of QAR data in this study were collected from three commercial aircrafts (Boeing 737-800) of a local airlines company. The original data is a CSV (Comma Separated Value) file with thousands of rows and columns. Therefore, VBA (Visual Basic for Applications) programing functions in Microsoft Excel was applied. In the final landing stage, aircrafts always fly within profile of a landing glide path; their position changes in the lateral axis are quite limited. Therefore, we focused on longitudinal and vertical parameters in this study. Finally, 19 columns of relevant original QAR data of every file were refined. 21 flight parameter variables were then selected and calculated as shown in the following table based on VBA programs. These parameter variables covered all flight and operational parameters in the critical visual and manual landing stages from the flare initial height to touchdown. Meanwhile due to flare maneuver would reduce the aircraft's descent rate to acceptable levels so that it settles gently on the main landing gear. It was seemed as one of the most skilled operation in flight [10], the pilot operation below 200 feet, especially the flare operation was selected as the main subject for analysis.

Among that the *Flare height* meant the height of initiating flare operation and *Flare time* meant the total time of aircraft flying from flare initial point to touch down point. It should be noted that the variable of flare time means the total time from flare initial point to touch down point. In addition, the flare operation initial point in this study is higher than the standard 30 feet in most flight manuals. This is because any slight backwards pulling of the control column could be recorded by a Quick Access Recorder, causing that the time and height of flare is earlier than theoretical value. The variable of *Touchdown Distance* and *Vertical Acceleration Touchdown* were two parameters using to determine long landing and hard landing. The *Vertical Acceleration Touchdown* meant the maximum value of vertical acceleration when the main landing gears touch the ground [11]. Based on the common statistical results of QAR data and monitoring criterion of aviation operators [12-14], the threshold of determining hard landing for this aircraft type was set as 1.4 g in this study.

Table 1. Selection of parameters

Classification	Name	Parameter name in QAR	Units
Kinematics & Performance	Flare height	RADIO HEIGHT	Feet
	Flare time	/	Second
	Groundspeed	GROUND SPEED	Knot
	Descent rate	VERT SPD	Feet/min
	Airspeed	AIR SPD	Knot
	Vertical acceleration	VERT ACCEL	g
	Touchdown distance	/	Feet
Operational Parameter	Throttle resolver angle	SELTD TRA FILTERED	Degree
	Control column position	CONTRL COLUMN POSN	Degree
	Control wheel position	CONTRL WHEEL POSN	Degree
	Control column force	CONTRL COLUMN FORCE	LBS
	Control wheel force	CONTRL WHEEL FORCE	LBS
	Flap handle position	FLAP HANDLE POSN	Degree
	Speed brake handle posi-	SPD BRAKE HANDLE	Degree
	Rudd pedal position	RUDD PEDAL POSN	Degree
Configuration & Attitude	Flap	FLAP	Degree
	Aileron	AILERON POSN	Degree
	Elevator	ELEV POSN	Degree
	Rudder	RUDD POSN	Degree
	Pitch angle	CAP DISP PITCH ATT	Degree
	Roll angle	CAP DISP ROLL ATT	Degree

2.2 Statistical Analyzing and Modeling

119 QAR data samples were divided into two groups with 65 cases of normal landing (Group 1) and the other one was 54 cases of hard landing (Group 2). QAR data of 65 normal landing events and 54 hard landings were regarded as two groups of independent samples. Each flight parameter variable of these 119 flights was also calculated by using VBA program.

First, the flight performance parameters of all flights were analyzed. For the aim of observing dynamic change of flight performance parameter variables in final landing phase and their differences between two groups, the altitude of 200 to 0 feet was divided into four flight phases (200-150-100-50-0 feet) and selected flight parameter was measured and compared in every phase. The multivariate analysis process of general linear model was introduced to compare the differences in the two groups.

Second, for the aim of finding the operation features of hard landing incidents and their correlations with landing performance, the statistical methods of variance analysis was used to find the difference of flare operation between normal landing and hard landing, including their parameter differences at flare initial point and in the whole flare process. One way ANOVA was used to examine variables which were subjected to normal distribution and non-parameter K-W test for other ones.

Third, aiming to find key flight parameters causing hard landing incidents, the logistic regression model on hard landing incidents was developed. In this study, the occurrence of hard landing was defined as a binary and dependent variable, where the value is 1 if it happened and 0 if it did not happen. The hard landing was judged by the parameter of vertical acceleration. We selected 17 flight parameters from Table 1 as original covariates in this logistical model, which including all operational parameters, configuration & attitude parameters and 3 kinematics parameters of groundspeed, airspeed and descent rate. Due to flare is a continuous operation from flare initial point to touchdown, the parameter value both at flare initial point and touchdown point were sampled in and there were 34 independent variables in total. The name and definition of each flight parameter is as showing in Table 1. The forward stepwise method was then performed. The likelihood ratio test (χ^2 difference) testing the change in –2LL (log likelihood) between steps was utilized to determine automatically which variables to add or drop from the model. The final predictor variables and coefficients of the model were obtained in the stepwise process. Simultaneously, the effectiveness of the model was checked and discussed below.

3 Results

3.1 Flight Performance Analysis

The variable of vertical acceleration is essentially both subjected to normal distribution and the results of Anderson-Daling test also proved it ($p > 0.05$). For the selected 119 samples, the mean and standard deviation of Vertical Acceleration Touchdown respectively was 1.387±0.082. The differences between 18 variables from 200 feet to touchdown were analyzed by using repeated measure and one-way ANOVA. Here only several important results regarding parameters of groundspeed, descent rate, control column and throttle are presented. Groundspeed and Descent rate are the two most flight performance parameters in landing and their change trend is as showing in Figure 1.

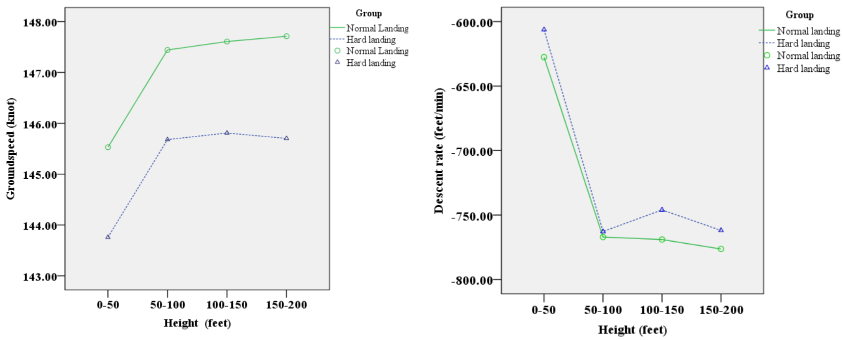

Fig. 1. Difference analysis of groundspeed and descent rate

As shown in Figure 1, the groundspeed of normal group is slightly greater than hard landing group. The difference of variable Groundspeed is not significant in the whole stage of 200-0 feet ($F(1,\ 117) = 1.763, p < 0.183$). The results of repeated measure ANOVA showed that the group effect of variable Descent rate is not significant ($F(1,\ 117) = 2.410,\ p = 0.123$). The descent rate of hard landing is slightly larger than the normal group before 50 feet, also the flare initial point, which changes a lot past 50 feet.

3.2 Flight Operation Analysis

Then, there were 65 normal landing samples (Group 1) and 54 hard landing samples (Group 2). The descriptive statistic on flare initial height and operation time of the two groups is as follows.

Table 2. Statistics on flare height and time

Group	**N**	**Flare Height** (*M* ± *SD, feet*)	**Flare Time** *(M* ± *SD, s)*
Normal Landing	65	52.169 ± 23.521	8.031 ± 2.076
Hard Landing	54	51.963 ± 20.175	7.722 ± 2.141

As seen in Table 2, there is no significant difference between the flare initial height of two groups, which are both around 50 feet ($F(1,\ 117) = 0.006, p = 0.941$). Meanwhile, the flare time of two groups also does not indicate significant difference ($F(1,\ 117) = 0.633, p{=}0.428$). Flare operation is considered one of the most technically demanding aspects of piloting. The results of the difference analysis on variables at the flare initial point are as shown in Table 3.

Table 3. Difference analysis on variables of flare initial point

Parameter Categories	**Variable Names**	**Group**	**Mean±SD**	***p*(ANOVA/K-W)**
Operation Parameter	Throttle Resolver Angle	Normal	49.277±1.786	0.069
		Hard	49.922±2.044	
	Control Column	Normal	1.066±0.882	0.342
		Hard	0.930±0.616	
	Column Force	Normal	2.111±1.010	0.620
		Hard	2.024±0.860	
	Control Wheel	Normal	0.052±10.179	0.586
		Hard	0.954±7.233	
	Wheel Force	Normal	0.001±0.462	0.624
		Hard	-0.038±0.375	
	Flap Handle Position	Normal	30.462±2.115	0.000
		Hard	32.963±4.609	
	Speed Brake Position	Normal	2.991±0.888	0.540
		Hard	2.898±0.740	
	Rudder Pedal	Normal	0.570±0.314	0.747
		Hard	0.555±0.142	
Configuration and Attitude	Elevator	Normal	2.423±1.088	0.376
		Hard	2.576±0.720	
	Aileron	Normal	1.383±2.124	0.441
		Hard	1.650±1.500	
	Flap	Normal	30.462±2.115	0.000
		Hard	32.963±4.609	
	Rudder	Normal	-0.134±0.693	0.600
		Hard	-0.192±0.484	
	Pitch Angle	Normal	1.600±0.603	0.012
		Hard	1.301±0.677	
	Roll Angle	Normal	-0.245±1.437	0.327
		Hard	-0.466±0.894	
Flight Performance	Air Speed	Normal	148.923±4.748	0.259
		Hard	147.907±5.003	
	Groundspeed	Normal	145.815±7.104	0.461
		Hard	146.833±7.883	
	Descent Rate	Normal	-803.077±121.718	0.638
		Hard	-813.481±117.407	
	Vertical Acceleration	Normal	1.051±0.040	0.298
		Hard	1.044±0.033	

For the normal landing and hard landing groups, there are only three variables representing the significant difference at the level of 0.05, which are *Flap Handle Position, Flap* and *Pitch Angle*.

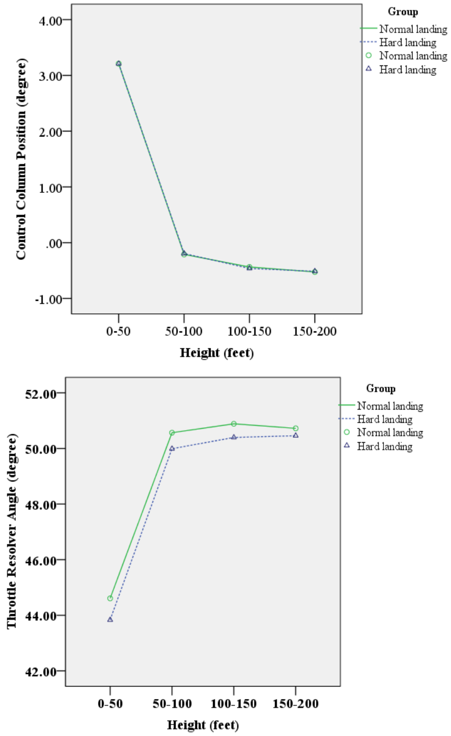

Fig. 2. Difference analysis of control column and throttle resolver angle

In Figure 2, the control column and throttle change greatly after passing 50 feet (flare operation initial point). There is no difference between the control column of the two groups ($F(1,\ 117) = 0.000, p = 0.998$). There is also no difference found for throttle operation before 50 feet ($F(1,\ 117) = 3.349, p < 0.07$). The difference is reflected after a flare starting when the pilot begins to decrease thrust.

3.3 Logistic Regression Model on Hard Landing

Table 4 shows the estimated parameters of the logistic model in predicting landing incident type (hard landing or normal landing). Three predictors were included in the final logistic regression model. The overall predictive percentage of the model was 72.6%, the sensitivity was 0.697and the specificity was 0.786.

As shown in Table 4, the Wald criteria indicated that *Flap Handle Touchdown, Pitch Angle Touchdown* and *Roll Angle Touchdown* significantly contributed to the occurrence of hard landings ($p < 0.01$). Nagelkerke's R^2 of 0.677 indicated a relatively strong relationship between predicting variables and hard landing.

Table 4. Logistic regression values of the predicting variables

Predicting variables	Wald (χ^2)	Adjust OR[a]	95% C.I.for OR[b]
Flap Handle Touchdown	11.107**	1.172	1.074-1.296
Pitch Angle Touchdown	18.613**	0.531	0.393-0.713
Roll Angle Touchdown	15.984**	2.229	1.489-3.281
Constant	3.469#	0.058	

** $p < .01$, * $p < .05$,# $.05 < p < .10$ and otherwise $p \geq .10$.

[a]Adjust ORs (odds ratio) predicted hard landing.

[b]Confidence interval.

4 Discussion and Conclusions

In aviation safety research, the focus has typically been more on aviation accidents where their occurrence rate has been decreased to quite a low level in most regions of the world. However, unsafe incidents have often been ignored due to the difficulty in obtaining and analyzing them in detail. Basing on flight QAR data, this study provided a new way to analyze unsafe incidents in the landing phase by considering a history of individual instances recorded during flight. The main findings in this study were concluded as following.

1. The results of multivariate analysis indicated that most flight parameter variables with differences appeared in the stage of 50 feet to touchdown. Theoretically speaking, many flight operations, including flares, need to be finished by pilots in just a few seconds. While aircraft in low speed flight is sensitive to wind and other weather factors, any small configuration changes during this stage could easily complicate the decision of the proper action to take at the decision point. Therefore, this phase is the most important operation stage and pilots should check the ratio of descent rate and groundspeed carefully at the point of 50 feet.
2. Flare would reduce the aircraft's descent rate to acceptable levels so that it settles gently on the main landing gear, it would greatly influence vertical acceleration through the two key factors of flare time and final flare pitch angle. The control column and throttle operation would affect landing performance conjointly. Pilots' quick and steady pulling up columns and softer throttle reduction are helpful for a better flare operation and better landing performance.
3. The logistic model showed that the vertical load of touching ground was actually linked with touchdown attitude and configuration closely, including three variables of pitch angle, roll angle and flap degree. Among these, the pitch angle of the aircraft is correlated with control column operation directly and therefore is a main external indication of flare. As a matter of fact, the correlations between pitch angle and vertical acceleration were strong at every stage from 200 to 0 feet.
4. These findings would be the basis of developing a mathematical and quantitative model for further revealing the relationships between pilot operation and landing

performance, which can also be applied in practice to prevent hard landing incidents and even landing accidents.

Acknowledgments. We appreciate the support of this work from the National Natural Science Foundation of China (No. 61304207, No.U1333112), the National Basic Research Program of China (No.2010CB734105) and the Fundamental Research Funds for the Central Universities (No. ZXH2012D001).

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