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QAR (Quick Access Recorder) 데이터 분석 기반 B777 Hard Landing Trend Analysis

B777 Hard Landing Trend Analysis based on Quick Access Recorder (QAR) Data

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[요 약]

2019년 IATA (International Air Transport Assosiation) 보고에 따르면 하드랜딩 사고 1건으로 인해 승객 41명의 사상자가 발생하였다. 이는 항공기의 불안정한 접근 상태에서 무리하게 착륙을 시도하여 발생한 하드랜딩 사고로 파악되었다. 하드랜딩의 주요 원인으로 불안정한 접근, 조종사의 플레어(flare) 실수, 잘못된 계획, 갑작스러운 기상 변화 등의 여러 가지 요인들이 있을 수 있다. 본 연구는 QAR (quick access recorder) 데이터 분석 시스템을 활용한 국내 항공사의 B777 기종에서 발생한 24건의 하드랜딩 이벤트를 항공기 강하율(descent rate), 비행 강하각 (flight path angle), 활주로 시단 통과 고도 (threshold passing altitude), 초기 플래어 고도 (initial flare altitude) 등의 분석을 통해, 하드랜딩의 원인이 항공기 접지 전 낮은 비행경로 (low vertical path)와 조종사의 적절지 못한 플래어 시기(late flare)로 식별하였다. 이에 하드랜딩 이벤트 경감 및 항행 안전 증진 방안으로 항공기의 안정된 접근 (stabilized approach) 과 특히 200ft 이하의 고도에서 착륙 시까지 항공기의 낮은 비행경로가 되지않도록, 일정한 강하 각 유지를 위한 조종사의 모니터링이 중요하다는 시사점을 도출하였다.

[Abstract]

According to the International Air Transport Association (IATA) 2019 Safety Report, one accident involving hard landing has caused 41 deaths. The accident was analyzed to be caused by the pilots' final judgement of making a forced the landing in unstabilized conditions. The factors leading to hard landings are unstabilized approach, misjudged flare, inappropriate planning, unexpected change in weather etc. This research aimed to look into detail the characteristics of hard landings by utilizing the quick access recorder (QAR) data of 24 recorded hard landing incidents of B777, such as descent rate, flight path angle, threshold passing altitude, initial flare altitude etc. The main causual factors were derived to be low vertical path and late flare. In order to promote proactive an precautionary measures, stabilized approach is emphasized as well as the continuous monitor of flight path angle below 200 ft to maintain proper vertical path.

Key word : Hard landing, QAR, FOQA (Flight Operation Quality Assurance), Low vertical path, Late flare, Safety report.

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I. Introduction

The International Air Transport Association (IATA) has reported in its Safety Report that 4.5 billion passengers were carried in 46.8 million flights in the year 2019. Out of those flights, there were 53 accidents, 9% of which were cargo and 91% passenger, causing a total of 240 fatalities.

The top three categories of accidents by the number of fatalities were loss of control, hard landing, and runway excursion. 4 cases of loss of control has killed 191 persons, 1 case of hard landing have killed 41 persons, and 2 cases of runway excursion has killed 3 persons[1].

The one case of hard landing that caused 41 fatalities was the Aeroflot flight SU1492. According to the Interim Accident Report, the flight departed Sheremetyevo airport, Moscow Russia, on May 18, 2019 18:00 local time. At around 9,000 ft, a flight control system malfunction occurred, and the pilots had to divert back to Sheremetyevo Airport.

The pilots of SU1492 did not perform the required fuel dumping and proceeded the approach overweight to runway 24L. At around 1,600 ft radio altitude, ground proximity warning system (GPWS) alerted “go-around, windshear ahead” however, the pilots ignored the warning and did not go-around. At around 300 ft radio altitude, the aircraft was flying well below the glideslope casing the “glideslope” warning to go off. The pilots once again ignored the warning and continued the approach. The unstable approach was concluded by a forced and bounced landing. The first touchdown recorded 2.55 G exceeding the hard landing limit value of 1.94 G [2]. The aircraft bounced 5-6 ft due to the shock from the touchdown and landed again nose gear-first, recording 5.85 G a value almost double the first touchdown. The aircraft bounced once again, this time higher up to 15~18 ft, and made the final touchdown recording 5.00 G. The main gear was damaged in the process causing the aircraft to collapse onto its body where a fire started, killing 41 passengers and crew [3].

The accident category distribution analyzed by IATA between 2015 and 2019 shows that the excursion of runway or taxiway, is most frequent taking 25% of all accidents. Hard landing accidents come in second place taking 13% of all accidents therefore may be considered one of critical hazards of aviation accidents [1].

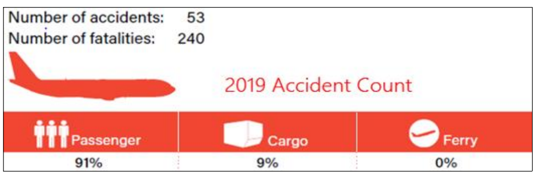

그림 1. 항공기 사고 및 발생률(IATA)
Fig. 1. Number of aircraft accidents & rates (IATA).

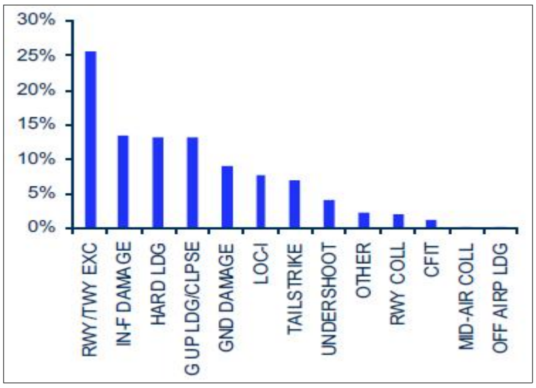

그림 2. 사고 유형별 분포 (IATA, 2015-2019)
Fig. 2. Accident category distribution (IATA, 2015-2019).

In order to identify and eliminate hazards in flight, the International Civil Aviation Organization (ICAO), recommends all commercial air operators with aircraft over 27,000 kg to establish and operate a safety management system (SMS) that records and analyses flight data[4].

This research aims to look into detail the characteristics of hard landings, utilize the quick access recorder(QAR) data of recorded incidents to analyze the occurrence trend, identify and proactively eliminate the causual factors, to derive implication for mitigations measures and safe airline operations.

II. Hard Landing Definition

When an aircraft is landing, it is like when a brick "hits" the airstrip. Actually, there is a clear sense from the strike on the bottom[5]. The G-sensors on board the aircraft detects and calculates the force exerted on the aircraft.

The G-value(G) that defines hard landings is the ratio of vertical force(F_v) to the weight(w).

$$G = \frac{F_v}{w} \tag{1}$$

Newton’s Second Law of Motion states that the net force applied to an object equals the resulting change in its momentum per unit time. In other words, the vertical force needed to land an aircraft equals to the change in momentum(Δp) of the aircraft over a certain period of time(Δt).

$$F_v = \frac{\Delta p}{\Delta t} \tag{2}$$

Momentum is expressed as a product of mass(m) and velocity(v). Here, the velocity is the vertical component of motion, or the vertical speed.

$$F_v = \frac{p_i - p_f}{\Delta t} = \frac{mv_i - mv_f}{\Delta t} \quad (3)$$

During touchdown, the vertical speed(v_i) is reduced to zero(v_f). The duration of touchdown, as measured by the G-sensors on board, is 0.1 seconds. Hence, the formula becomes :

$$F_v = \frac{mv_i}{0.1} \quad (4)$$

The weight is a product of mass and the gravitational acceleration(g). The gravitational acceleration is 9.8m/s^2.

$$w = mg \quad (5)$$
$$= m9.8$$

Substituting (4) and (5) in (1) :

$$G = \frac{F_v}{w} \quad (6)$$
$$= \frac{mv_i/0.1}{m9.8}$$

The mass cancels out hence, the formula becomes a function solely depending on the vertical speed(v).

$$G = \frac{v}{0.98} \quad (7)$$

It can be seen by the equation that the G-value becomes a function of the initial vertical speed observed by the QAR. Table 1 shows the relationship between the initial vertical speed and the G-value. The light shaded area is defined as a category of hard landing in terms of vertical speed. The dark shaded area is defined as hard landing in terms of G-value. Refer to 3-3 Hard Landing Event Criteria.

III. QAR Flight Data Analysis Program

3-1 Introduction to QAR

표 1. 강하율과 G값의 계산값
Table 1. G-value in relations to vertical speed.

fpm	fps	m/s	sec	F_v	G-Value
160	2.67	0.81	0.10	8.13	0.83
180	3.00	0.91	0.10	9.14	0.93
200	3.33	1.02	0.10	10.16	1.04
220	3.67	1.12	0.10	11.18	1.14
240	4.00	1.22	0.10	12.19	1.24
260	4.33	1.32	0.10	13.21	1.35
280	4.67	1.42	0.10	14.22	1.45
300	5.00	1.52	0.10	15.24	1.56
320	5.33	1.63	0.10	16.26	1.66
340	5.67	1.73	0.10	17.27	1.76
360	6.00	1.83	0.10	18.29	1.87
380	6.33	1.93	0.10	19.30	1.97
400	6.67	2.03	0.10	20.32	2.07
420	7.00	2.13	0.10	21.34	2.18
440	7.33	2.24	0.10	22.35	2.28
460	7.67	2.34	0.10	23.37	2.38
480	8.00	2.44	0.10	24.38	2.49
500	8.33	2.54	0.10	25.40	2.59
520	8.67	2.64	0.10	26.42	2.70
540	9.00	2.74	0.10	27.43	2.80
560	9.33	2.84	0.10	28.45	2.90
580	9.67	2.95	0.10	29.46	3.01
600	10.00	3.05	0.10	30.48	3.11

The QAR is a flight data recording device installed onboard the aircraft. The access to the system is designed to be quick and easy, and saved flight data can be downloaded from the aircraft[6]. When a flight reaches the home base of either Gimpo international airport (RKSS/GMP) or Incheon international airport (RKSI/ICN), the QAR flight data can be downloaded via wireless communication or a storage medium. The collected data is sent in electronic file format to the analysis system of flight operation quality assurance (FOQA)1). All events occurred during the flight is analyzed using the data, and not limited to the pilots' input, other factors such as the instrument procedures, landscape, weather, etc. are considered. The analyses are used to find trends in events and identify the causes for deviating from the standard operating procedures (SOP). By eliminating these causes the system is used to promote proactive identification of hazards and improve safety of flight[7].

The result of QAR is used not only in the FOQA, but also the maintenance, flight technical team, and flight management team. The maintenance team uses the records to solve technical issues of the aircraft. Such activities decrease the unscheduled maintenance, hereby increasing the aircraft availability. The QAR data is also used in other purposes such as the monitoring of

1) FOQA (Flight Operation Quality Assurance) : Proactive safety program operated by the operator to monitor the QAR data insuring safety in flight.

aircraft performance and management of fuel efficiency.

3-2 Legal Basis of Utilizing the QAR Data

In accordance with ICAO Document Annex 6, the operators of commercial transport aircraft exceeding 27,000 kg are required to have installed on board the aircraft flight data recorder (FDR) or digital flight data recorder (DFDR), cockpit voice recorder(CVR), and to operate a flight data analysis program(FDAP). The Federal Aviation Administration (FAA), United States, through its research, also concluded that the wide implementation of FOQA program could significantly increase the safety of flight and promotes voluntary participation of FOQA program to the air operators[6].

The use of flight data must comply with the de-identification & non-punishment rules. The data needs to be independent from the operator and pilot(s) unless it is required that the specific operator and/or pilot(s) need to be reached for the safety measures or mitigation. Unless the operator and/or pilot(s) deliberately violated the SOP and/or committed criminal actions, the flight data must not be used for disadvantage or punishment[8].

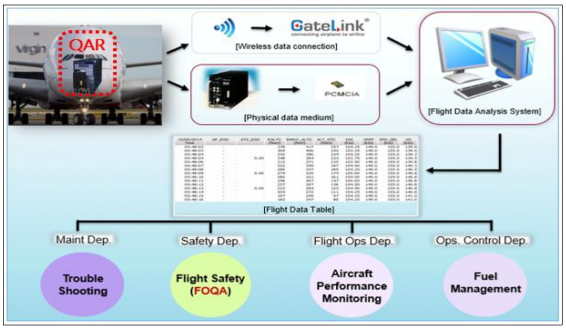

그림 3. QAR Data 분석 프로그램
Fig. 3. QAR Data Analysis Program.

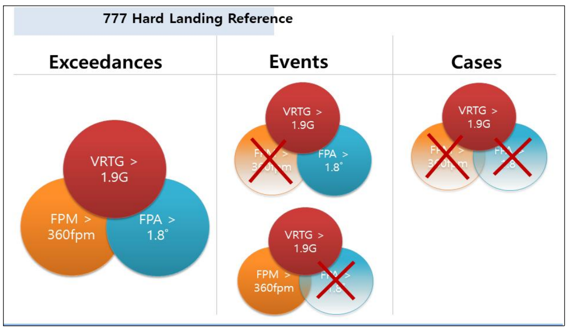

그림 4. Hard landing 정의 기준
Fig. 4. Hard landing reference.

In the Korean aviation safety law, enforcement no.130-2, the operator of aircraft exceeding 20,000 kg must have in operation a FDAP. The aviation safety law no.58-4 states that when the operator is creating a FDAP, it must have regulations on the use and non-disclosure of flight data analysis results[9]. Based on these regulations, all Korean air operators with aircraft over 20,000kg must have a FDAP.

3-3 Hard Landing Event Criteria

In the QAR data analysis, an *"event"* is when a flight breaches the safety margins set on top of that defined in the SOP. These event data are used to identify the trend in flight safety, and as data by the SMS.

An *"exceedance"* is when the breach significantly exceeds the SOP limits enough to danger the safety of flight[10], and requires immediate mitigation measures such as pilot training or revision of SOP.

Hard landings generate high load on the aircraft gear, wings, and fuselage. This may cause damage and/or deformation of major components potentially jeopardizing the aircraft performance. In order to identify these risk factors QAR data analysis is done. The data used to identify hard landings are the vertical acceleration factor(G-value), the descent rate(fpm), the flight path angle (FPA) data from the moment of touchdown.

Events are when the vertical deceleration(G-value) exceeds 1.9 G in the QAR and either the FPA or the fpm breaches its limits. *Exceedances* are *Events* which the aircraft exceeds 360 fpm and has FPA greater than 1.8 degrees, from 0.5 seconds to the aircraft touchdown. According to Boeing's maintenance records of hard landings, the pilots' typically report hard landing at around 240 fpm landing[11].

IV. Boeing 777 Hard Landing QAR Data Analysis

This research is based on 24 hard landing events recorded in an airline in Korea between 2017 and 2019. In order to narrow down the scope of research, only the events of Boeing 777-200ER and Boeing 777-300ER were taken into account.

The relations between the vertical G and descent rate, FPA and glideslope deviation, the change in wind vector during flare, threshold passing height, moment of flare, aircraft speeds, hard landing report etc. were analyzed to find causual factors contributing to hard landings, and finally to suggest proactive and precautionary measures to mitigate hard landings.

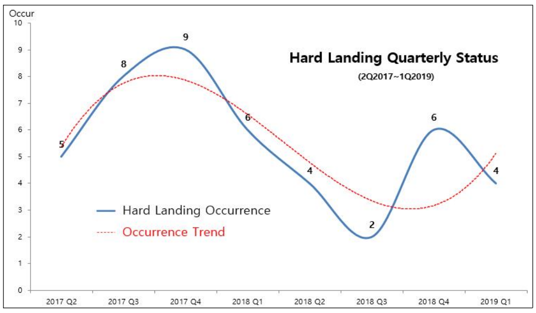

그림 5. B777 분기별 Hard landing 발생 건수 및 경향성
Fig. 5. B777 Hard landing quarterly occurrence & trend .

4-1 Boeing 777 Hard Landing Trend

Figure 5 shows the trend of hard landing events from 2nd quarter of 2017 to 1st quarter of 2019. In the 3rd and 4th quarter of 2017, the trend showed an increase where 17 hard landing events were recorded in total.[2)] The company sent notices to all pilots of the hard landing trend information as a preventative measure and was able to steadily decrease the event occurrence in the coming 4 consecutive quarters. The number went down to 2 in the 3rd quarter of 2018 where it increased again in the following quarter. The 2 years trend also shows the events tend to increase approaching the Winter season due to the unstable atmosphere. By informing the pilots of seasonal trend, the pilots could take more caution in the Winter season.

4-2 Descent Rate & Vertical G

The flare moment recommended by Boeing for the B777 series is at 30 ft radio altitude. Proper flare will decrease the rate of descent to around 100 fpm by touchdown[12].

Figure 6 shows the relationship between the peak descent rate 0.5 seconds before touchdown and the G-value of hard landing events. It can be observed that in most of the cases high rate of descent was maintained until the moment of touchdown.

4-3 Flight Path Angle & Vertical G

Per given ground speed, the G-value increases when the FPA increases. The increase in FPA leads to the increase in fpm. In the ideal case where the FPA and groundspeed remain constant the vertical speed can be calculated using the below equation.

2) "B777 FOQA Trend Analysis", Airline SMS Conference Presentation (2019)

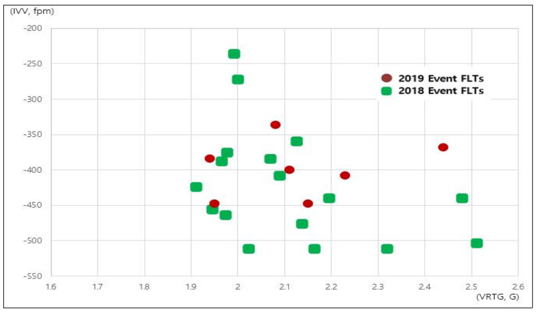

그림 6. Hard landing시 강하율과 G값의 관계
Fig. 6. Descent rate & vertical G at hard landing.

표 2. FPA와 GS에 따른 강하율 계산값
Table 2. Vertical speed per FPA and GS.

GS (kt)	Flight Path Angle (degrees)												
	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
130	138	184	230	276	322	368	414	460	506	552	598	644	690
131	139	185	232	278	324	371	417	463	510	556	602	649	695
132	140	187	233	280	327	373	420	467	514	560	607	654	701
133	141	188	235	282	329	376	423	470	517	565	612	659	706
134	142	189	237	284	332	379	426	474	521	569	616	664	711
135	143	191	239	286	334	382	430	477	525	573	621	669	716
136	144	192	240	288	337	385	433	481	529	577	625	674	722
137	145	194	242	291	339	388	436	484	533	581	630	679	727
138	146	195	244	293	342	390	439	488	537	586	635	683	732
139	147	197	246	295	344	393	442	492	541	590	639	688	738
140	148	198	247	297	346	396	446	495	545	594	644	693	743
141	150	199	249	299	349	399	449	499	549	598	648	698	748
142	151	201	251	301	351	402	452	502	552	603	653	703	754
143	152	202	253	303	354	405	455	506	556	607	658	708	759
144	153	204	255	305	356	407	458	509	560	611	662	713	764
145	154	205	256	308	359	410	461	513	564	615	667	718	770
146	155	206	258	310	361	413	465	516	568	620	671	723	775
147	156	208	260	312	364	416	468	520	572	624	676	728	780
148	157	209	262	314	366	419	471	523	576	628	681	733	785
149	158	211	263	316	369	421	474	527	580	632	685	738	791
150	159	212	265	318	371	424	477	530	584	637	690	743	796

Table 2 shows the calculated values per typical B777 ground speed on touchdown. The vertical speed(v_v) can be calculated according to the ground speed(v_{gs}) and flight path angle (Θ) :

$$v_v = \tan(\theta) v_{gs} \quad (8)$$

Table 2 shows the calculated vertical speeds per FPA and ground speed. The light shaded area is defined as a category of hard landing in terms of vertical speed. The dark shaded area is defined as hard landing in terms of FPA. Refer to 3-3 hard landing event criteria.

The actual ground speed and FPA constantly change as the pilots make inputs for the flare[13] therefore, are different from the ideal calculated values. The actual cases are shown in Figure 7. One case in 2019 is a typical example how reality differs from the calculations. The flight had a 2.37° FPA until the pilot yanked the yoke making an abrupt pitch change in the last moment. The aircraft pitch went up to 5.6° and the recorded peak FPA 0.5 seconds before touchdown was only 1.32° however, the flight still recorded a hard landing at 2.4 G

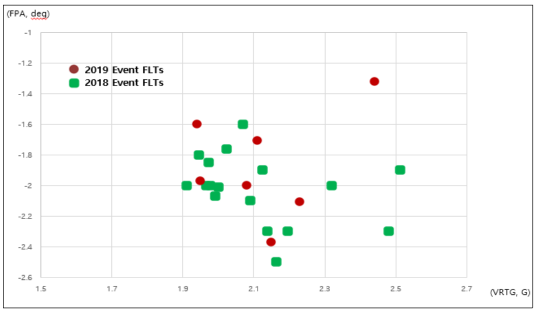

그림 7. FPA와 G값 관계
Fig. 7. FPA & vertical G.

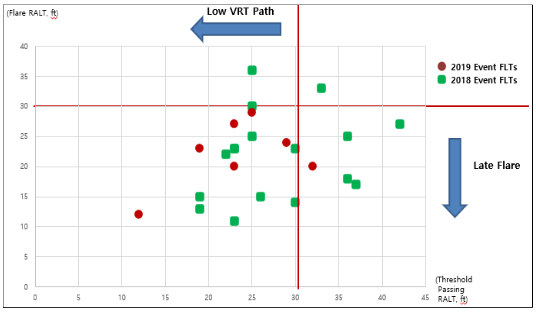

그림 8. Threshold 통과와 flare 고도 관계
Fig. 8. Threshold passing & flare altitude.

4-4 Threshold Passing & Flare Altitude

The threshold passing height and flare altitude analysis showed that most of the hard landing events had a late flare. While 30 ft is the typical flare altitude, all but two had flare above 30 ft. Most of the flights showed that the threshold passing altitude was below the normal 50 ft. Figure 8 suggests that low threshold passing height is one of causual factors to late flare.

4-5 Low Vertical Path

The vertical deviation had an increasing trend below 200ft in the hard landing events. Figure 9 shows the vertical deviation from the glide path below 200 ft. The vertical axis is in unit of “dot” deviation. The data was recorded every 50 feet of descent where it shows that most flights had an increase trend in the vertical deviation below 200 ft. Although it is difficult for the pilot to monitor the glideslope deviation below minimums, the fact that 77% of the hard landing events had low approach between 100~200 ft should be noted.

4-6 Hard Landings with Wind Variation

A total of 7 events had a headwind component change over 10 kts. Figure 10 shows the pitch change per wind change during flare.

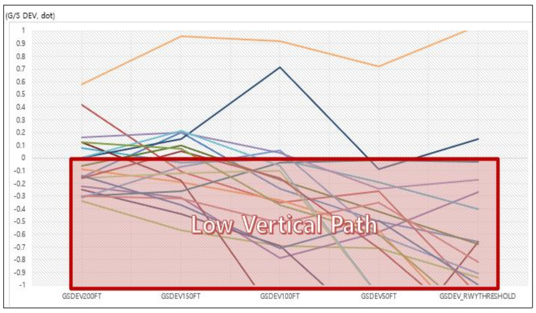

그림 9. 200 ft부터 RWY threshold까지의 G/S deviation
Fig. 9. G/S deviation from 200 ft to RWY threshold.

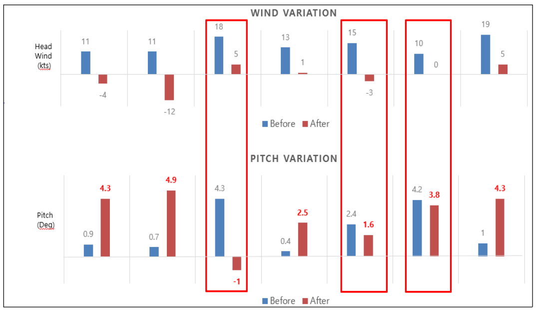

그림 10. Pitch와 정풍 성분 변화 (50 ft 미만)
Fig. 10. Pitch trend and headwind component variation (below 50 ft).

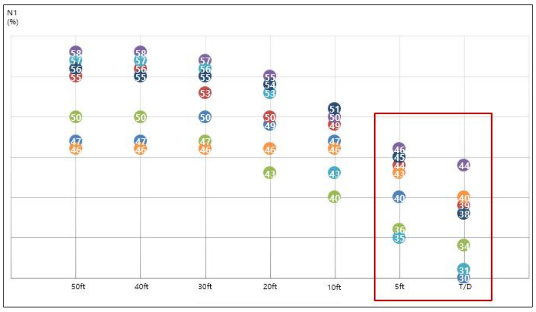

그림 11. 50 ft에서 접지까지 N1 추진력 트렌드
Fig. 11. N1 Thrust trend from 50 ft to T/D.

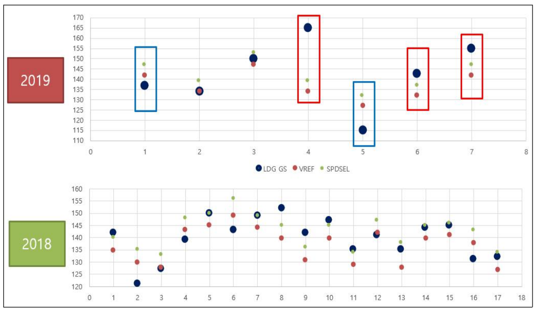

그림 12. Hard landing 과 ground speed 관계
Fig. 12. Hard landing ground speed trend.

In order to compensate the decrease in headwind component, abrupt pitch up controls were made. In three cases, the pitch control was insufficient, and the aircraft eventually had a decrease in pitch. In one of the cases, due to an abrupt change in wind, the pilot made and excessive pitch down control after 4.3 degrees of maximum pitch, and the aircraft recorded a 1.98 G when the nose gear touched down.

Figure 11 is the N1 control input in flares with over 10 kts headwind component decrease. In order to compensate to the decrease in headwind component, the thrust was maintained at 40% at 10 ft in all of the cases however, 4 cases made a power on landing on touchdown.

Changes in the headwind component requires more attention in pilot-controlled flare. Figure 12 shows the Groundspeed, VREF and selected speed for each case (horizontal axis). In hard landings from 2019, the groundspeed and VREF showed significant difference. Case 4 recorded 2.44 G making the oxygen masks to drop. The groundspeed was recorded at 31 kts above VREF. Many flights showed that groundspeed and the Indicated airspeed can differ significantly below 200ft. This affects the 3° glide path and finally the touchdown FPA, requiring more attention from the pilots.

4-7 B-777 Hard Landing Pilot Report

The primary source for a suspected hard landing is the flight crew. Most pilots report a hard landing when the sink rate exceeds approximately 240 fpm. On-board accelerometers are notoriously unreliable indicators of heavy landings because of their low sampling rates (8 or 16 samples/sec) and because they are located near the CG and may not represent the peak loads in other parts of the aircraft[10].

A total of 36 flights(including cases insufficient for *events* and *exceedances*) have recorded over 1.9 G in the two years scope(Figure 13). 16 cases(44%) have been logged in the maintenance logbook as suspected hard landing. Only 5 cases(14%) were written in the air safety report (ASR).

Out of the pilot reported cases (suspected hard landing and ASR cases) the QAR data shows 10 cases with over 1.9 G, 6 cases between 1.7 G and 1.9 G, and 5 cases below 1.7 G(Figure 14). This suggests that the G-values of less than 1.7 G are still enough to be recognized in the cockpit as hard landings.

The accumulated stress in the structure of the aircraft due to hard landings is a potential hazard in the health of the aircraft. This could be mitigated by the pilot's appropriate loggings and subsequent maintenance activities.

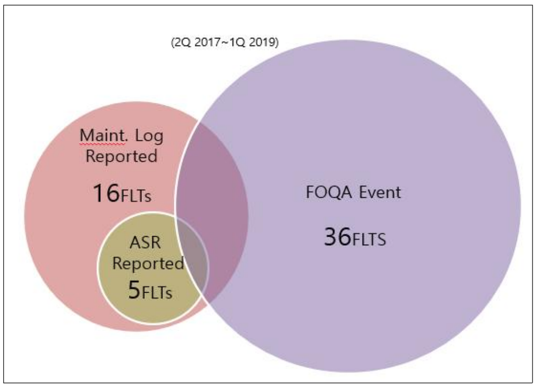

그림 13. 조종사 보고 Hard landing 사례 현황
Fig. 13. Hard landing pilot report status.

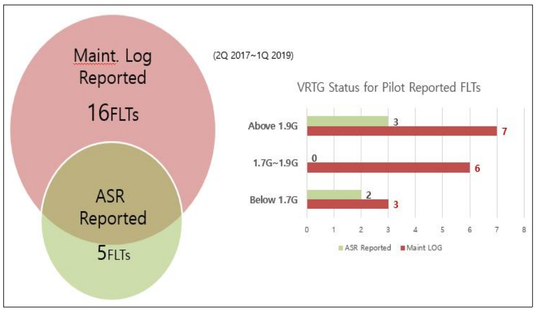

그림 14. 조종사 보고 사례의 G값 현황
Fig. 14. Pilot reported flight's vertical G status.

The lack of reporting by the pilots suggest that the pilots were reluctant to report the event. This is because the experience showed that the reports were not de-identified, and punishments or disadvantages were given to the pilots.

V. Conclusion

This research aimed to look into detail the characteristics of hard landings, utilize the QAR data of recorded incidents to analyze the occurrence trend, identify the causual factors, and finally promote proactive and precautionary measures. 24 hard landing events recorded by the QAR were analyzed. By investigating the relations between the vertical G and descent rate, FPA and glideslope deviation, the change in wind vector during flare, threshold passing height, moment of flare, aircraft speeds, hard landing report etc. the characteristics of hard landings were analyzed.

77% of the events were found to have had low and unstable vertical path between 200 ft and touchdown. In the analysis between the threshold passing height and the moment of flare, 22 events were recorded to have started the flare below 30 ft; late flare. The research provided that the low vertical path and late flare are two of the main contributing factors in hard landings. The mitigations are suggested as follows:

First, the pilot flying (PF) must maintain stabilized approach in order to avoid low vertical path and late flare. The constant vertical path monitoring below 200 ft is highly recommended.

Second, the pilot monitoring (PM) must actively call out any deviation from the SOP in the flight path, speed, sink rate etc. for the PF to take immediate and appropriate countermeasures, or go-around. The option of going around is available until the thrust reversers or ground spoilers are deployed.

Lastly, unless the pilots have intentionally violated the SOP, or committed criminal acts, the QAR data should not be used in any way or format for disadvantage or punishment to the pilots or the companies. The de-identification and non-punishment characters are the life of the voluntary reporting system. Active hard landing reports by the pilots allow timely inspection and maintenance on the potential structural damages or stress applied on the aircraft, thereby decreasing the chance of aircraft failure.

The limitation faced in the research was the lack of data. The data sample was from a single airline over the period of two years. The data was incomplete in terms of details limiting further breakdown of each event. The research in insufficient to represent the overall trend and analysis of hard landings in Korea. For future research, QAR data from all the airlines in Korea will need to be provided through the national level of aviation safety management program.

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