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Airframe Usage and Operational Loads of ASM/Lead Aircraft in USFS Service

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Results are presented for three Beechcraft King Air models being flown in firefighting operations by USFS. Data is presented for 3,829 flights recorded on C90A, C90GT, and E90 models. For 40% of the flights, the aircraft was being ferried from one location to another, while all remaining flights had firefighting operations. Usage data is presented and compared to limits for each model. Cumulative occurrences of incremental vertical load factors per 1000 hours are presented for the overall flight. Both gust and maneuver loads are presented in frequency in AGL altitude bands. Comparisons are made with typical commercial usage.

I. Nomenclature

n = Vertical Load Factor
Δn_z = Incremental Vertical Load Factor
V = Indicated Airspeed
V_{MO} = Maximum Maneuvering Airspeed

II. Introduction

UNITED State Forest Service (USFS) utilizes a large number of aircraft in support of firefighting operations. These aircraft may be used in roles that are different from that for which the aircraft were designed. In 2004, National Transportation Safety Board (NTSB) issued Recommendation A-04-29 (Reference 1). This recommendation stated that, due to the operational loads experienced during firefighting operations, USFS should develop maintenance and inspection programs for the aircraft. Based on this recommendation, one action taken by USFS was to install Digital Flight Data Recorders (DFDRs) on the aircraft in its fleet (Reference 2). Data has been collected for many years from aircraft flying in firefighting operations.

One aircraft group of particular interest was the Beechcraft King Air models, which are used by USFS to perform a variety of missions. Ferry/passenger missions are those in which the aircraft is moved from one base to another. These flights do not contain firefighting operations and resemble most closely the flights for which the airplane was designed. During Air Tactical Group Supervisor (ATGS) missions, the aircraft loiters over the fire zone and observes and monitors operations. These flights consist of many turns over the fire zone. Aerial Supervision Module (ASM) missions are flown at lower altitudes than ATGS, but still contain numerous turns as the fire situation is being assessed. During lead missions, the aircraft escorts an airtanker over the fire, at altitudes as low as 150 feet AGL. The lead aircraft demonstrates the flight path as well as indicates the location of the retardant drop. The lead aircraft works with many airtankers during a single flight, resulting in many descents and climbs, as well as turns.

Preliminary analysis was performed by Hawker-Beechcraft Corporation (HBC) in 2009 to determine if the operational loads in USFS service were a concern (Reference 3). The results obtained during that analysis showed more severe loads as well as a higher frequency of loads for airplanes flown in USFS operations. Based on the results found by HBC, a more in-depth analysis was done by Wichita State University (WSU). The WSU study included more flights and data from more airframes than that available for the HBC study. The primary goals were to analyze

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the usage and the operational loads. The usage analysis would result in comparison of the design of the aircraft with how the aircraft was used in USFS missions. The operational loads were separated into those due to gusts and those resulting from maneuvering the aircraft and compared to other sources.

III. Method of Analysis

A. Flight Data

Flight data was recorded on DFDRs made and supported by Appareo Systems. The channels available are shown in Table 1, and all were recorded at a constant 8 Hz. Some channels were calculated in post processing while others did not contain useful information.

B. Distance

True airspeed was included in the available data. The information recorded was confirmed using temperature, pressure, and indicated airspeed, all of which were recorded. The distance traveled was found by integrating true airspeed over time.

Table 1. Channels Recorded by the DFDR

Channel	Parameter	Units
1	Line Number	---
2	Elapsed Time	Seconds
3	Bay Door[1]	Binary
4	Discretes[1]	Binary
5, 7	GPS Latitude and Longitude	Degrees
6	Elevation	Feet
8, 9	Pitch, Roll	Degrees
10	GPS Speed	Knots
11	Vertical Speed[2]	Feet per Minute
12	Heading	Degrees
13-15	Pitch, Roll, and Yaw Rate	Degrees per Second
16-18	Longitudinal, Lateral, and Normal Acceleration	g
19-21	True[2], Equivalent[2], and Indicated Airspeed	Knots
22	Course Direction	Degrees
23-24	Pitot and Static Pressure	Inches of Mercury
25	Outside Air Temperature	Degrees Celsius
26-27	Horizontal[1] and Vertical[1] Accuracy	Millimeter
28	Weight on Wheels[3]	Binary
29	Discrete1[3]	Binary
30	Discrete2[1]	Binary
31	Discrete3[4]	Binary
32	Discrete4[1]	Binary

[1] Did not contain any useful information or data was a duplicate of another channel.
[2] Quantities calculated in post processing.
[3] Squat switch data could be in either, both, or neither of these channels.
[4] Contained flap deflection in the 2014 data, otherwise did not contain useful information.

C. AGL Altitude

AGL altitude proved to be an important parameter for the ASM/Lead airplanes. Due to the nature of the flights, lead airplanes could be flying at an MSL altitude of several thousand feet while at an AGL altitude of only a few hundred feet. Terrain elevation was found using the GPS position of the airplane and the National Elevation Dataset (NED), which is maintained by the United States Geological Survey (USGS). The information in that dataset was available for the majority of the United States with a resolution of 30 feet (Reference 6).

D. Load Factors

Vertical load factors were recorded at 8 Hz throughout the flight. In order to separate the gust and maneuver loads, the two-second rule was used (Reference 7). This method was developed using aircraft much different than the ASM/Lead airplane and it was later suggested that this may not be the best method for separation loads (Reference 8). However, it was proven that varying the duration led to little difference between the cumulative gust and maneuver loads. Therefore, WSU used the two-second rule to separate the gust and maneuver loads, which is consistent with the method used in previous studies.

The peaks and valleys in the vertical acceleration were found using the peak-between-means method (Reference 9), as illustrated in Fig. 1. This method states that only one peak or valley is counted between two successive crossings of the mean. Irrelevant loads around the mean were removed from the data by defining a threshold zone (dead band) of ±0.05 g around the mean.

IV. Results and Discussion

A. Airframe Usage

Flight data was recorded during years 2009-2014 on seven aircraft: three C90A, three C90GT, and one E90. A total of 3,829 flights were recorded, consisting of 7,076 flights hours and 1,290,516 nm.

The results were separated into ferry flights and flights containing USFS missions. The ferry flights were those in which the aircraft was moved from one location to another. While the flights with USFS missions were those in which the aircraft was flown in support of firefighting operations. The number, duration, and distance for each type of flight are shown in Table 2. As can be seen, 41% of the flights were in the ferry category. Flights with USFS missions accounted for 59% of the total.

Information about flap deflection was not included in the recorded data until after the 2013 firefighting season. Therefore, of the flights included in this study, only one year contained flap deflection information. In addition, the signal was discrete, so the flap deflection angle was not known, only whether or not the flap was deployed. The number, duration, and distance for flights with and without flap information are shown in Table 3. For 81% of the flights, information about the flap deflection was not recorded. Only 19% of the flight files contained flap deflection data.

Ferry flights had an average duration of 1.28 hours, and usually had one flap deployment during the flight. However, firefighting missions had an average duration of 2.24 hours and contained many flap extensions and retractions. The numbers of flap deployments per 100 ground-air-ground cycles and per 100 flight hours are shown in Table 4. Table 5 shows the percentage of ferry and firefighting flights with a certain number of flap deployments. In fact, nearly 13% of the firefighting flights had more than 15 flap deployments. Tables 4 and 5 clearly demonstrate that the flaps usage was very different between ferry and firefighting flights.

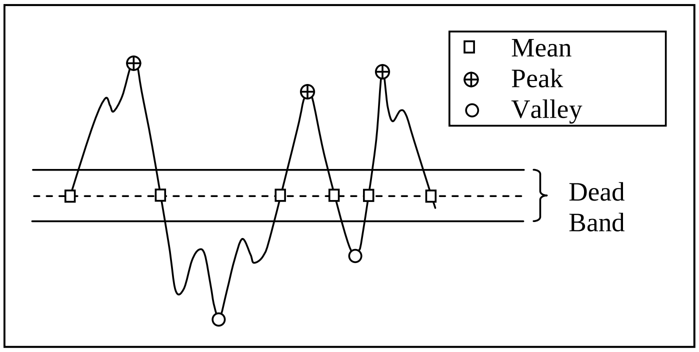


Fig. 1 Schematic of the Peak-Between-Means Method

Table 2. Ferry and Firefighting Flight Information

Model	**C90A**	**C90GT**	**E90**	**Total**
Number of Ferry Flights	551	935	78	1,564
Duration (hr) For Ferry Flights	741	1,165	102	2,008
Distance (nm) For Ferry Flights	168,248	265,105	21,198	454,551
Number of Flights With USFS Missions	827	1,366	72	2,265
Duration (hr) of Flights With USFS Missions	1,800	3,047	221	5,068
Distance (nm) of Flights With USFS Missions	308,120	492,966	34,879	835,965

Table 3. Flights With and Without Flap Data

Model	**C90A**	**C90GT**	**E90**	**Total**
Number of Flights With Flap Information	399	340	0	739
Duration (hr) With Flap Information	726	582	0	1,308
Distance (nm) With Flap Information	133,756	101,447	0	235,203
Number of Flights Without Flap Information	979	1,961	150	3,090
Duration (hr) Without Flap Information	1,815	3,632	323	5,770
Distance (nm) Without Flap Information	342,613	656,623	56,077	1,055,313

Table 4. Number of Flap Deployments per Mission Type

Flap Usage	**Ferry**	**Firefighting**
Per 100 GAG Cycles	103.6	722.1
Per 100 Flight Hours	88.9	340.6

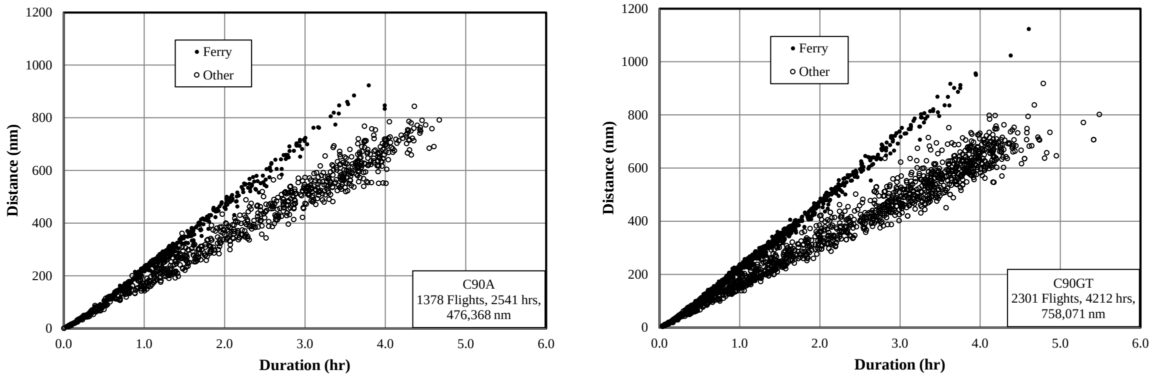
Table 5. Flap Deployment per Flight

	Percentage of Flights with Number of Flap Deployments				
	1 to 2	**3 to 5**	**6 to 10**	**11 to 15**	**>15**
Ferry	99.3	0.7	0.0	0.0	0.0
Firefighting	29.5	21.4	23.1	13.0	13.0

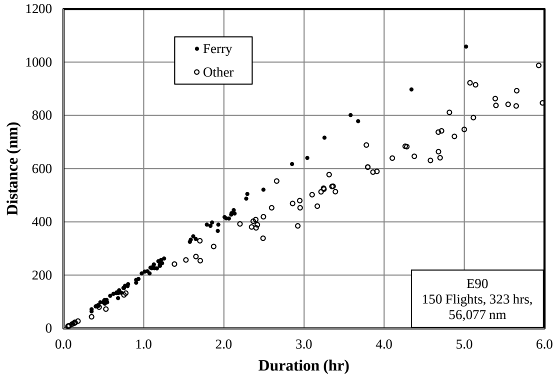
In Fig. 2, the correlation between distance and duration is presented for each model. This figure clearly shows that the ferry flights exhibited a tighter correlation between the distance and duration than firefighting missions. The flights consisting of ferry operations also had a higher maximum average indicated airspeed.

Maximum MSL altitudes and coincident indicated airspeeds are shown in Fig. 3. The maximum altitude did not exceed 30,000 feet. In addition, the highest maximum altitudes were associated with the C90GT. Figure 4 shows the maximum indicated airspeeds and coincident MSL altitudes. In a noticeable number of cases, the V_{MO} of 226 KIAS was exceeded. This over-speeding occurred as often for ferry flights as for firefighting missions. However, it was apparent that for firefighting missions, a large number of flights were flown at a maximum indicated airspeed below 200 KIAS.

Figure 5 shows the maximum and minimum vertical load factor versus corresponding indicated airspeed for each flight. This data is presented for each model separately along with the limits corresponding to gross and empty weights. Weight was not a recorded parameter and, therefore, was not known at each of the occurrences. The flight data on which these results were based was recorded prior to the 2014 fire season and did not contain information about flap deflection. In one case, the vertical load factor for a C90A exceeded the positive limit of +3.29 g. All other maximum and minimum vertical load factors remained within the limits of -1.33 g and +3.29 g.



(a) C90A **(b) C90GT**



(c) E90

Fig. 2 Flight Duration and Coincident Flight Distance, Overall Flight

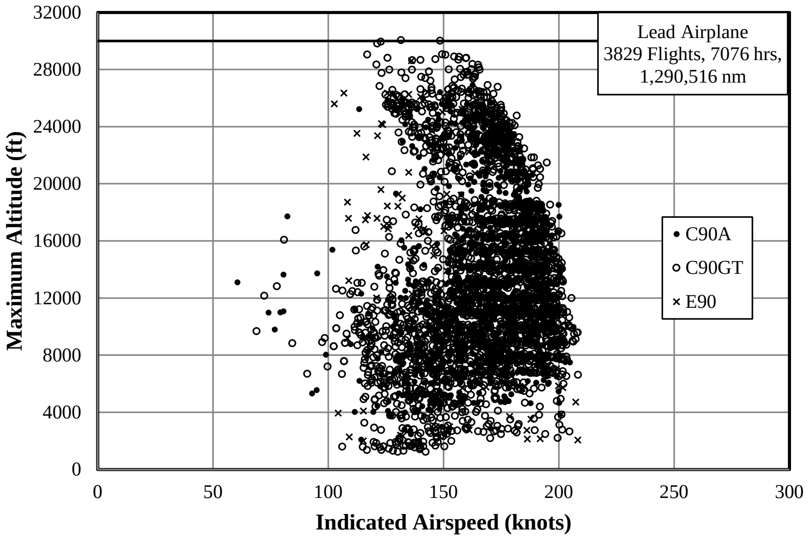


Fig. 3 Maximum MSL Altitude and Coincident Indicated Airspeed, Overall Flight

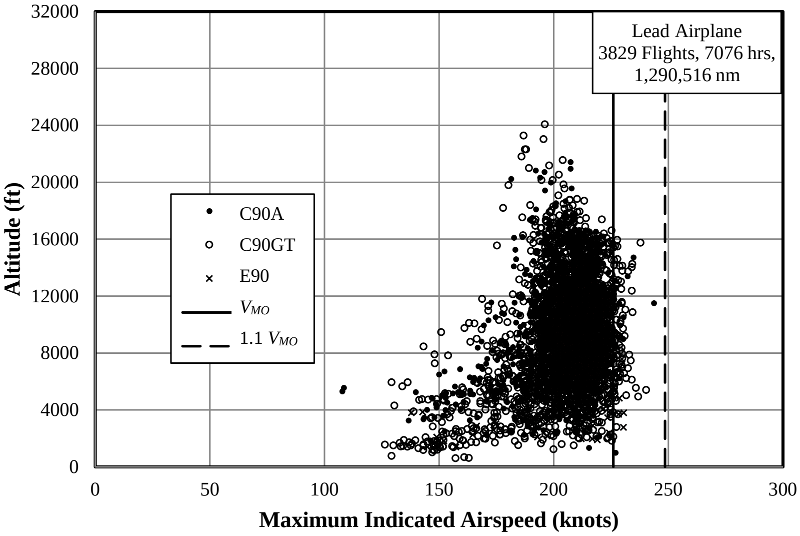
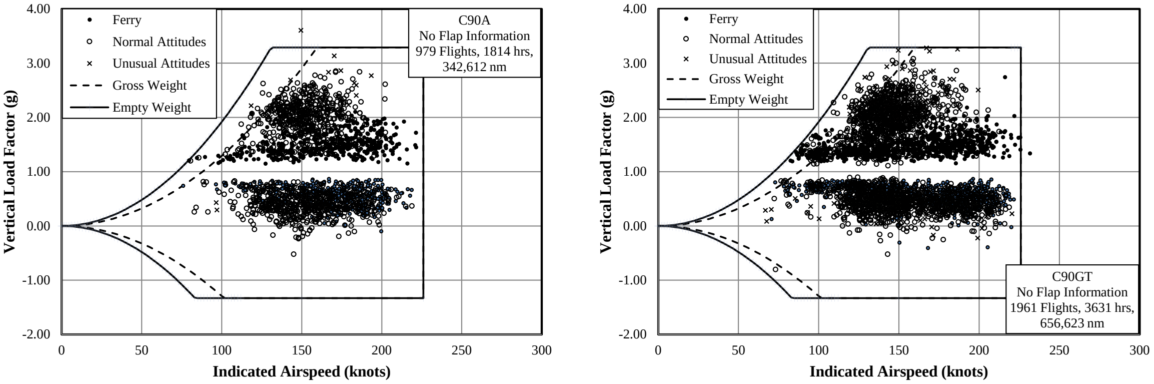
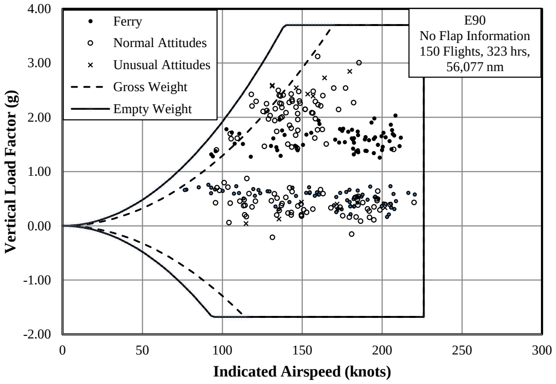


Fig. 4 Maximum Indicated Airspeed and Coincident MSL Altitude, Overall Flight



(a) C90A **(b) C90GT**



(c) E90

Fig. 5 *V-n* Diagram by Model, Overall Flight without Flap Information

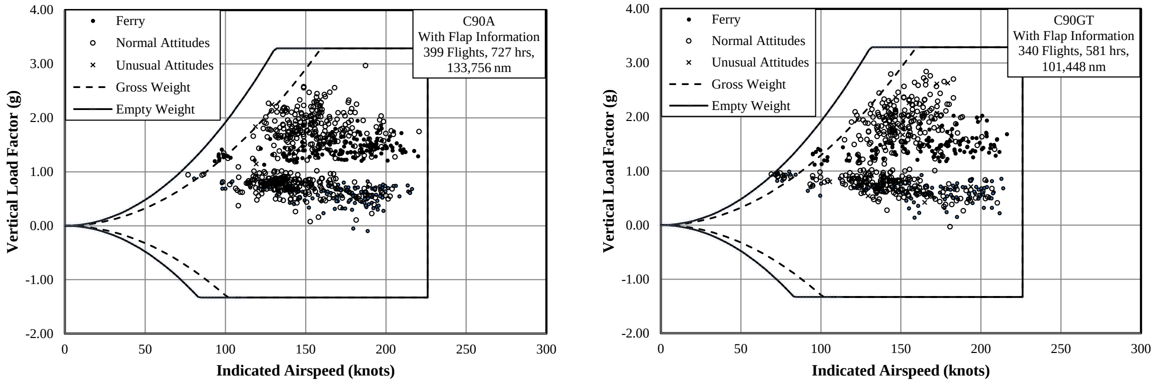
One concern for the data recorded prior to 2014 was that the maximum load factor and indicated airspeed limits change when the flaps are deflected. Therefore, between the 2013 and 2014 fire seasons, the discrete flap channel was added to the recorded information.

Figures 6 and 7 show the maximum and minimum vertical load factors versus corresponding indicated airspeed for the 2014 fire season. The E90 model was not used during the 2014 fire season and, therefore, these figures only include information for the C90A and C90GT. The limit load factors were never exceeded when the flaps were retracted. However, when flaps were deflected, there were many cases in which the limit load factors were exceeded. Almost all of the exceedances occurred during flights containing firefighting missions. Confirming this is the observation that most of the exceedances occurred at indicated airspeeds of 120-170 knots, which is the range associated with lead missions, when flaps are used in the first detent. While the load factor limits did not change with different flap deflection angle, the airspeed limits did. Therefore, there are two limits for the maximum indicated airspeed in Fig. 7, which correspond to different flap detents.

B. Operational Loads

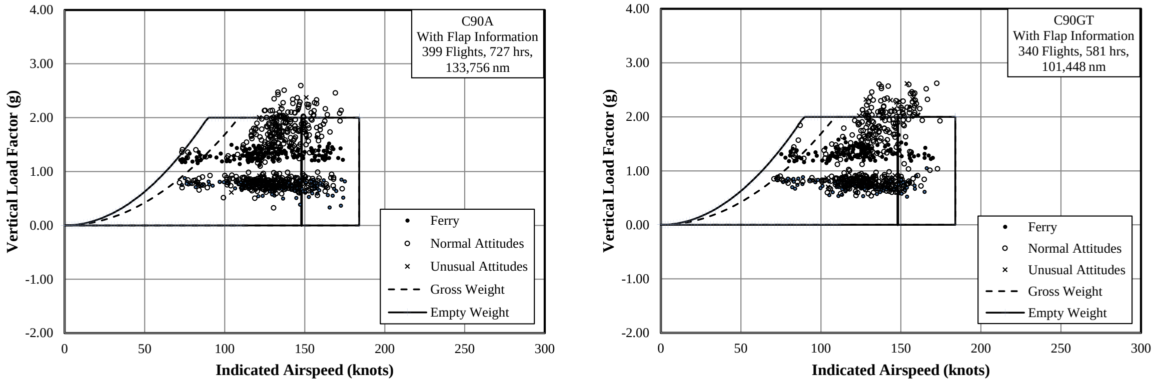
Due to the nature of the USFS missions, it was determined that the gust and maneuver loads for the ASM/Lead airplanes correlated much better with AGL altitudes instead of MSL altitudes (Reference 6). Therefore, the flights loads presented here were plotted in AGL altitude bands, which are shown in Table 6 along with duration and distance flown in each band.

Cumulative occurrences of gust load factors per 1000 hours are presented in Fig. 8. The results show a dependence on AGL altitude, with the lower altitudes having a higher number of occurrences. Also, in the two lowest altitude bands, the figure is not symmetric, with positive gust loads occurring more frequently than negative. At altitudes above 19,500 ft AGL, the data was scarce, which led to some scatter in the results.



(a) C90A **(b) C90GT**

Fig. 6 *V-n* Diagram by Model, Overall Flight with Flaps Retracted



(a) C90A **(b) C90GT**

Fig. 7 *V-n* Diagram by Model, Overall Flight with Flaps Deflected

Table 6. Summary of Durations and Distances in AGL Altitude Bands

Altitude (ft)	Duration (hr)	Distance (nm)
0 – 500	367	52,368
500 – 1,500	1,790	267,085
1,500 – 4,500	2,503	416,324
4,500 – 9,500	943	198,679
9,500 – 14,500	543	127,781
14,500 – 19,500	593	145,651
19,500 – 24,500	297	72,988
Above 24,500	40	9,639
Total	7,076	1,290,515

Figure 9 shows the cumulative occurrences of maneuver load factors per 1000 hours. Again, the results indicate a dependence on AGL altitude, with the lower altitudes having a higher number of occurrences. This suggested that the aircraft was flown more aggressively below 4,500 ft AGL than it was above that altitude. Again, data was scarce at altitudes above 19,500 ft AGL, leading to more scatter in the results.

For Fig. 10, all altitude bands were combined for exceedance spectra of gust and maneuver loads per 1000 hours. In this figure, the USFS loads are compared to maneuver loads of MIL 8866 (Reference 10). While MIL 8866 is limited to maneuver loads of larger aircraft, the comparison is included here to illustrate the differences. At incremental load factors less than +1.5 g, the USFS fleet experienced higher maneuver load factors.

For Fig. 11, the gust and maneuver loads were combined for USFS missions. The combination of all USFS load factors were compared to the typical commercial usage (Reference 3), preliminary analysis of USFS data done by HBC (Reference 3), and data presented by Hall (Reference 11). It is apparent that the results presented here agree well with those of the preliminary analysis done by HBC. It is also apparent, that the results presented here do not agree with those of Hall. This source of this discrepancy is not known, but it was expected because the results of Hall also disagreed with earlier heavy airtanker analysis (Reference 12).

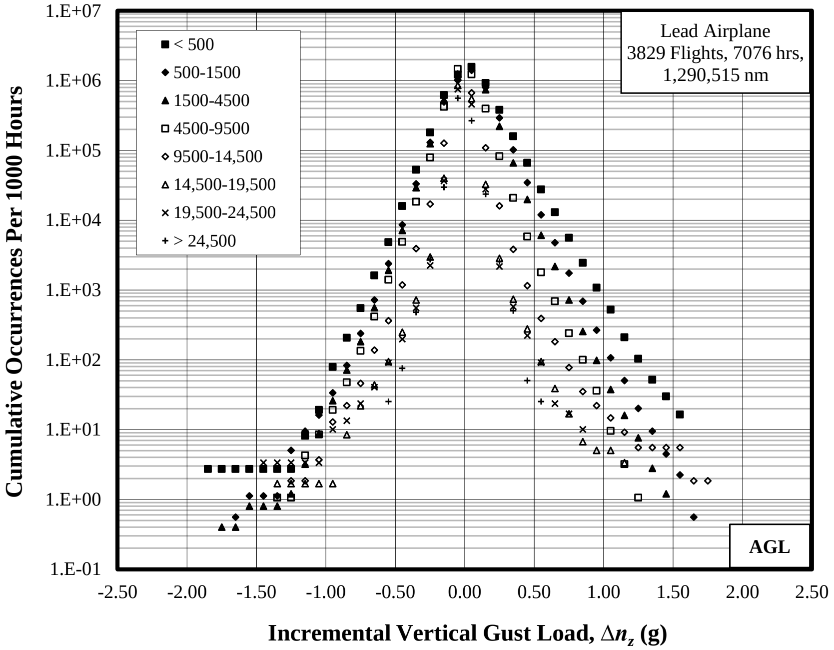


Fig. 8 Cumulative Occurrences of Incremental Vertical Gust Load Factor Per 1000 Hours, Overall Flight

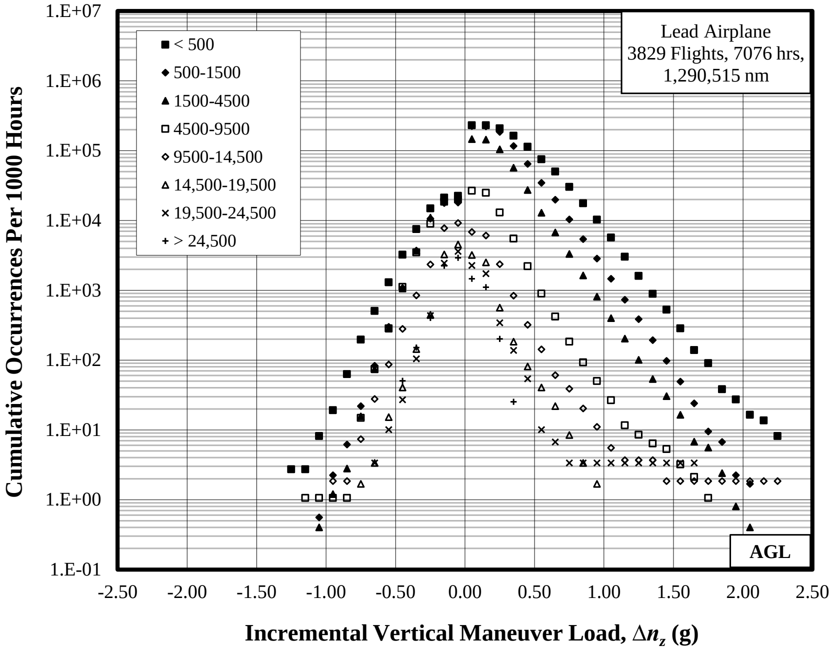


Fig. 9 Cumulative Occurrences of Incremental Vertical Maneuver Load Factor Per 1000 Hours, Overall Flight

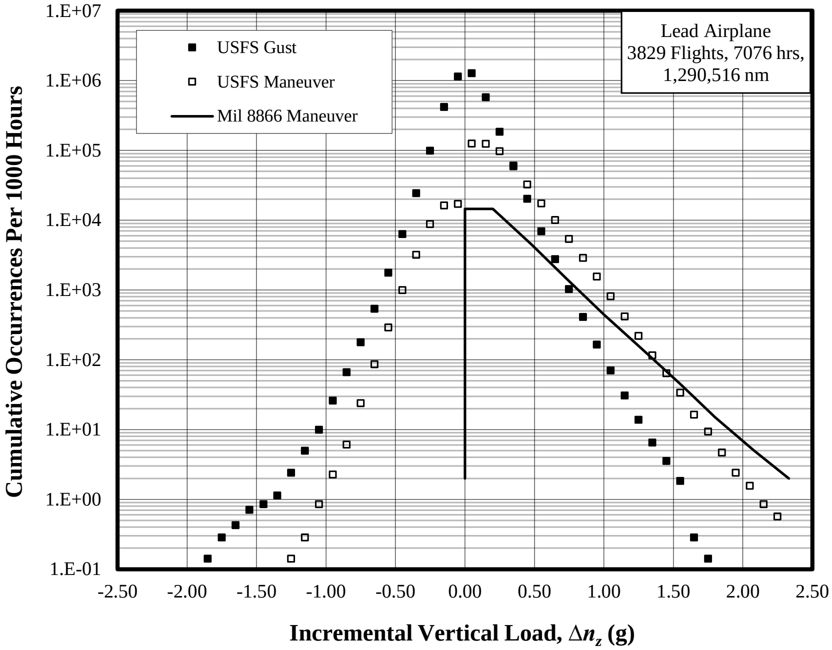


Fig. 10 Cumulative Occurrences of Incremental Vertical Load Factor Per 1000 Hours Compared with MIL 8866 Maneuver Loads, Overall Flight

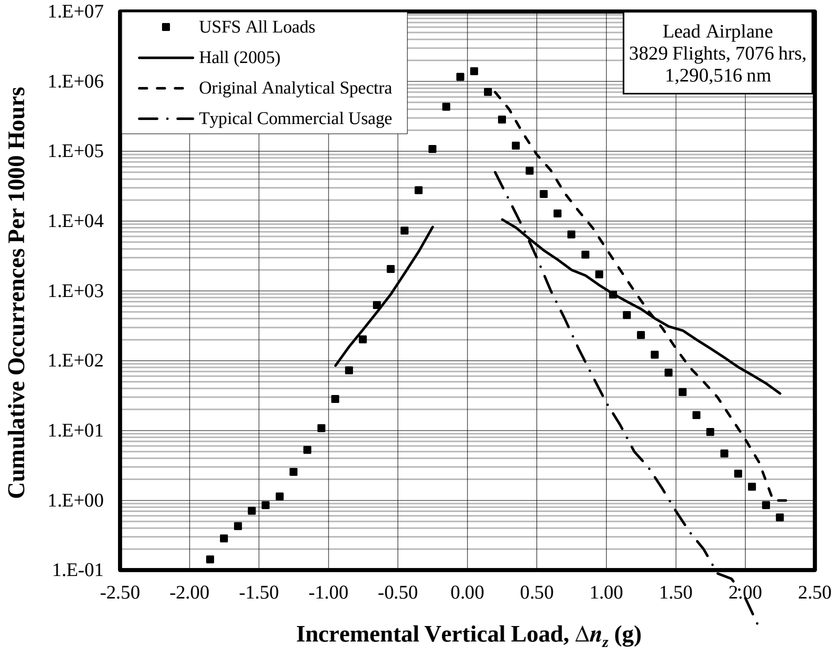


Fig. 11 Cumulative Occurrences of Incremental Vertical Load Factor Per 1000 Hours, Overall Flight

V. Conclusions

Results were presented for Beechcraft King Air models being flow in USFS firefighting operations. Data was recorded on three C90A, three C90GT, and one E90. A total of 3,829 flights were recorded 2009-2014, consisting of 7,076 hours and 1,290,516 nm. For 41% of the flights, the airplane was ferried from one location to another. The remaining 59% of the flights contained firefighting operations. Only 19% of the flights contained information about the flap deflection.

Usage results indicate that the maximum altitude to which the aircraft was flown was 30,000 feet MSL. The maximum indicated airspeed was shown to exceed V_{MO} in a significant number of flights. The maximum vertical load factors and coincident indicated airspeeds were presented, along with limits for each model. In cases when information about the flaps was not available, the limit load factor was assumed to be that for when flaps were retracted. In one case, the limit load factor was exceeded in a C90A. The data from 2014 included information about whether or not the flaps were deployed, and the limit load factors were set accordingly. The 2014 data showed that in many cases, the maximum allowable load factor was exceeded when flaps were deflected.

Cumulative occurrences of incremental load factors per 1000 hours were examined for the overall flight. Both gust and maneuver loads were shown to increase in frequency as AGL altitude decreased. The cumulative occurrences of gust and maneuver loads, as well as a combination of the two, were compared with those from other references. Combined gust and maneuver load factors were shown to occur more frequently than those of typical commercial usage.

VI. Acknowledgement

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