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A Case Study of B752 Wake Vortex Strength Evolution with and without Winglet Retrofit

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Smoke flow visualization of the vortex core conducted by the Federal Aviation Administration at Idaho Falls, Idaho, 1990
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Abstract

A case study involving B752's wake turbulence strength measurements with and without winglet retrofit was conducted. The results suggest that retrofitted B752 winglets have no discernable influence on the wake of this specific aircraft. These results also imply that the vortex spacing is not meaningfully affected by the addition of winglets on the B752, at least at high lift configuration when the wings tend to be more loaded inboard. It should be kept in mind that the results presented herein are specific to B752 and might not be completely extendable to other airframes or wingtip devices without further case studies.

Introduction

Aircraft models with retrofitted wingtip devices such as winglets (herein defined as near-vertical wingtip extensions) have a documented effect on improving aircraft fuel efficiency and range over the non-winglet retrofitted counterparts, with the understanding that these devices fundamentally reduce induced drag. There is a desire to understand whether winglets have other benefits, such as modifying the aircraft wake turbulence hazard. The objective of the current study is to provide such an assessment, using data collected from commercial aircraft operations, to address if there is a discernable benefit or disadvantage of winglets on wake turbulence hazard for distances relevant to wake turbulence separation standards. Both arrival and departure near-ground-effect wake turbulence data from B752 are used for this investigation.

Data Description

The B752 data selected for this case study came from the FAA WTR&DP. Data were collected at San Francisco International Airport (SFO). Both the data collection and post processing were utilizing the WindTracer® Pulsed LIght Detection and Ranging (LIDAR) infrastructure from Lockheed Martin Coherent Technologies, Inc.

Choice of B752

The choice of this dataset is motivated by two reasons. Firstly, when B752s entered into service, they were not equipped with winglets. The data collection periods (to be described later) correspond to when the airline industry was actively transitioning from non-winglet variant of the B752s to the retrofitted version of the aircraft. Consequently, wake data from both variants of the B752s are captured. Secondly, the wingspan of the B752 with winglet retrofitted is a significant (approximately 8 percent) enlargement over the wingspan without winglet[1]. As the wake decay time scale is proportional to the third power of wingspan[2] (more precisely vortex spacing, which is a fraction of wingspan), the theoretical worst-case consequence of the wingspan increase will manifest in a significantly slower decay rate for the winglet variant of the B752 (which is to be tested). The Boeing B752 winglet retrofitting program therefore provided a unique case study opportunity on the wake turbulence decay evolution impact from winglet retrofits.

Arrival Data

The arrival dataset for this study came from approaches to SFO Runway 28s at a nominal altitude of 128 feet above the local terrain. The date ranges for the arrival dataset were first from June to July of 2010, and then from February to December of 2012. It may be of interest to note that this data collection configuration involves measurements over the San Francisco Bay.

Departure Data

The selected departure dataset was from SFO Runway 01s operations during the periods of December 2007 to December 2008, and then from September to November of 2009. The median altitude of the B752 departures used in the study was 115 feet above local terrain. The locations of the arrival and departure data collection are shown in Fig. 1.

Figure 1. Locations of the LIDARs and associated scan orientations (red lines) in the current study (superimposed on Google Earth image)

Winglet Equipage Identification

The wake turbulence database included Mode S code, from which additional information such as the make-model-series, aircraft registration number and winglet retrofitting history can be retrieved. A combination of winglet retrofitting records/histories from airlines (obtained via FAA WTR&DP) and FAA certification databases were used to cross reference with an aircraft-spotting-enthusiast website, to isolate the winglet vs non-winglet B752 cases in the SFO wake turbulence data.

Additional Details

Both arrival and departure data used in the study are restricted to wake tracks with wind magnitude less or equal to 10 knots. The source of this wind information is the Automated Surface Observing System (ASOS). Since the arrivals on runway 28s and departures on runway 01s is a common configuration at SFO, and the wind condition typically would represent headwind operations for arrivals and crosswind operations for departures, a wind restriction allows a better comparison between the arrival and departure wake characteristics, although such a comparison is not the main purpose of the effort.

Furthermore, only cases that are longer lasting (defined by this study as B752 wakes that last at least 100 seconds) are considered. The philosophy of selecting these longer lasting tracks is to ensure that wakes that have the higher potential of presenting a risk are compared. It is also important to keep in mind that just because vortices are long lasting, that in itself does not automatically translate to a hazard as wake turbulence risk is a complex interplay of decay, transport, procedures and encounter geometries, training, etc. The final wake track counts used in this study are summarized in Table 1, where the WL and NWL notations represent respectively Winglet and Non-Winglet cases.

Table 1. Wake track data count summary

Wake Tracks	WL	NWL
Arrival	225	2275
Departure	40	329

Hypothesis to be Tested

The wingspans of WL and NWL variants of the B752 are 41.08 m and 38.05 m, respectively[1]. For the purpose of predicting the maximum possible effect of the wingspan extension due to winglet retrofitting, it is assumed that both variants have their vortex spacing as $\pi/4$ of their respective wingspans. In effect, it is assumed that the 8 percent wingspan increase from the winglet translates to the same percentage of vortex spacing enlargement for the winglet equipped B752. The theoretical prediction that 8 percent wingspan increase from winglet retrofitting manifested itself in 8 percent vortex spacing is first shown. It is sufficient to show the prediction for the arrival case only, as the departure prediction would follow the same relative behavior.

Using the framework of the engineering model described in Ref. 3, speed input from the effort described in Ref. 4 and with landing weight assumed to be 90 percent that of the maximum landing weight, the winglet vs non-winglet variants of the B752 would exhibit the relative behavior shown in Fig. 2.

Note that Fig. 2 indicates the B752 retrofitted winglet variant would have a lower initial circulation and a slower decay rate compared to its non-winglet counterpart. This prediction is next compared with measurements. The comparison is done in terms of both measured initial circulation as well as the decay history.

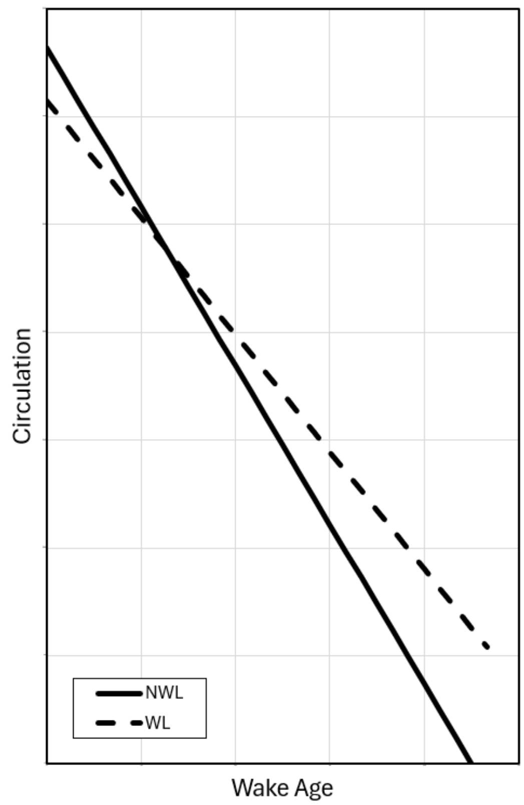

Figure 2. The predicted relative decay behavior of the B752 non-winglet vs retrofitted winglet variants

Data Analysis and Comparison with the Hypothesis

The measured initial circulation for both non-winglet and retrofitted winglet variants are actually the same. Both variants have measured median initial circulation of 305 m^2/s. This is an indicator that the 8 percent wingspan extension due to winglet retrofit may not result in a corresponding decrease in the initial circulation for the winglet variant.

The circulation evolution data described earlier whose data counts are summarized in Table 1 are then characterized via a process termed *gamma binning*[5,6]. The conventional and common way of generating a median circulation decay curve is to take the median of the data at each given time bin. As time progresses, there are fewer and fewer data points in each time bin, and the resulting median is essentially weighted only by the surviving vortices with the result that the vortices that have demised make no contribution to the median circulation values in the later time bins. The median circulation values in each later time bin are therefore not representative of the true overall decay. By performing the binning in circulation where the median time for each circulation bin is computed, the resulting decay curve is less biased towards only the remaining surviving wakes. Results from the early wake age portion of the *gamma binning*, however, may be counter-intuitive at a first glance, since circulation values higher than the time-binned median initial circulation values may be computed. It is for this reason that subsequent results from *gamma binning* of the relevant B752 data are presented without the initial higher gamma bins so that focus can be paid to the portion of the data relevant to wake turbulence separation .

The resulting *gamma binning* median decay curves are shown in Fig. 3. All of the decay curve plots in the manuscript have been generated with the same scales. The measurements showed that the non-winglet and winglet variants do not have a relative decay trend suggested by the prediction in Fig. 2. The arrival plot, which contains more data for the comparison, essentially showed the circulation rate of change for the two variants to be the same. The same conclusion is applicable for departure comparison, even though the smaller departure dataset resulted in less smooth curves compared to the arrival comparison. Overall, the data for both arrival and departure showed the wingspan extension as the result of the B752 winglet addition does not produce a different wake strength evolution relative to the non-winglet variant.

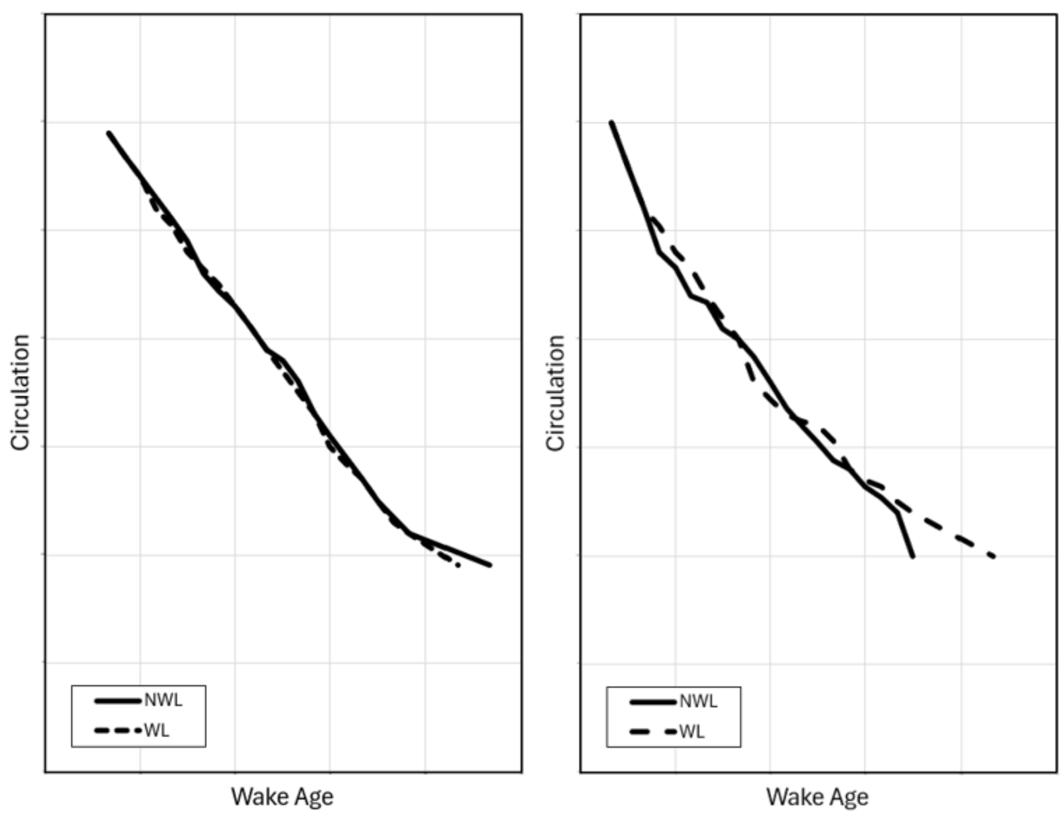

Figure 3. Comparison of B752 wake measurements from non-winglet vs winglet variants. The left and right figures are the arrival and departure cases, respectively

Since the anticipated difference from Fig. 2 is not observed in the flight data, the results also implied that B752 vortex spacing is not as affected by winglet extension as theorized; the 8 percent wingspan increase from winglet retrofitting does not translate to a corresponding 8 percent increase in vortex spacing. This conclusion can also be visualized graphically by adjusting the non-dimensional decay rate of the model used to produce Fig. 2 to best-fit the non-winglet variant of the arrival *gamma-binning* decay curve data (in the linear decay region), and then use the resulting non-dimensional decay curve to predict the decay curve with 8 percent vortex spacing increase (i.e., the upper bound of the hypothesized winglet variant behavior). In addition to specifying the decay rates, the initial circulation for the two variants would also be needed. In this exercise, both variants will use their respective circulation values from the measurements, which are the same. Fig. 4 shows the result of this exercise.

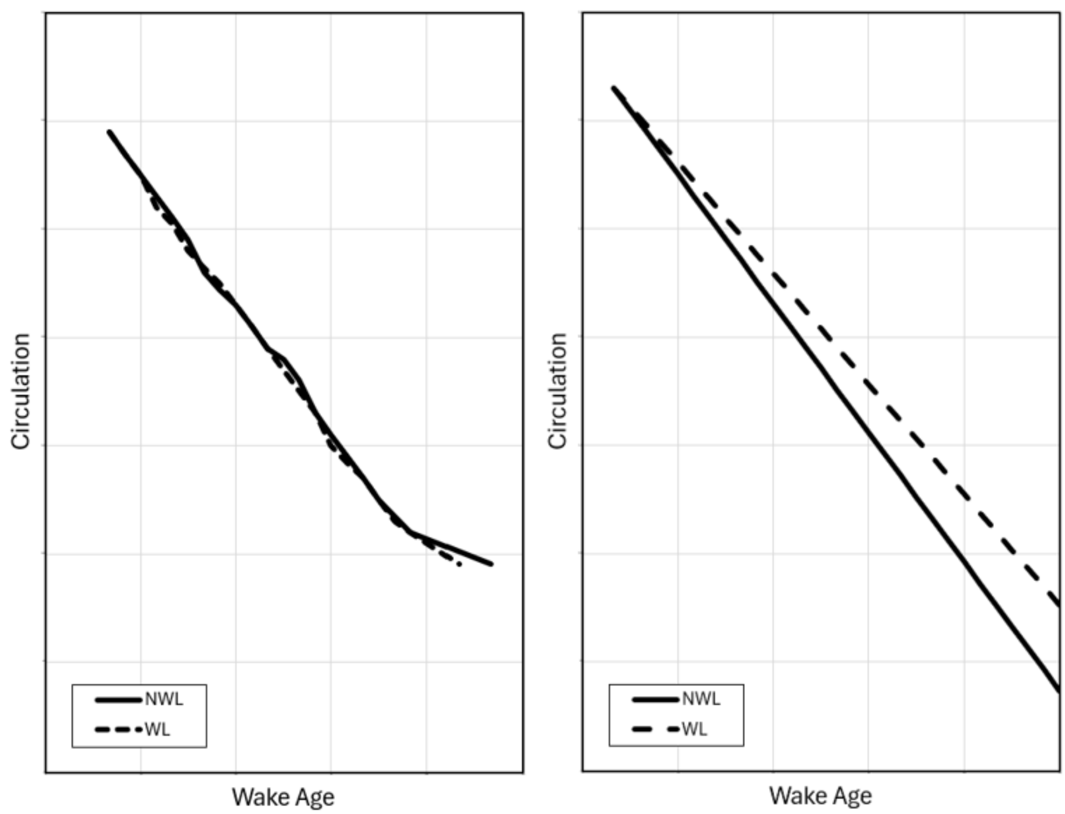

Figure 4. Comparison of B752 arrival wake measurements vs prediction that involves matching the decay rate for the non-winglet data

The prediction showed that if winglet extension has the maximum impact assumed herein, it would have a noticeably different decay characteristic relative to the NWL variant. It should be noted that although elliptical wing loading has been assumed, the relative behavior would still be the same if a different fixed fraction of vortex spacing to geometric wingspan were used. The predicted relative behavior for departure wake was also made, using the same modeling framework and assumptions, with the result that the relative behavior between WL vs NWL cases on departure follows the same trend as Fig. 2 and is omitted for brevity.

Additional Consideration

As B752's WL and NWL variants essentially have the same vortex spacing (or effective aerodynamic wingspan from a wake turbulence perspective) as suggested in Fig. 3, the maximum possible impact from winglet extension on initial circulation is next examined using the following heuristic argument. Assuming that the impact of the winglet addition is completely manifested in induced drag reduction, and classical aerodynamics expresses the relationship between induced drag and lift[7] as:

$$CD_i = \frac{CL^2}{\pi\, AR} \qquad (1)$$

where CD_i, CL and AR are respectively the coefficients of induced drag and lift, and aspect ratio of the wing.

Since CL is proportional to the initial circulation[8], Γ_0 , then

$$\Delta CD_i \propto \Delta\Gamma_0^2 \qquad (2)$$

Note that Eq. (2) can also be obtained from the consideration that the induced drag is manifested as the kinetic energy of the vortex in the cross flow plane[9].

For similar style winglets, the range of the induced drag reduction has been cited to be between 4 to 7 percent at high lift configurations[10,11]. Therefore, Eq. (2) would suggest that the initial circulation change due to the B752 winglet retrofitting is at most less than 3 percent range. Using the engineering model of Ref 1, with the inputs that the winglet variant of the aircraft having up to 3 percent initial circulation decrease and fixing vortex spacing at the value of the non-winglet variant, the resulting decay trend is practically undisguisable with the non-winglet variant. The data also showed that there is no meaningful difference in either the initial circulation as well as the downstream evolution as seen in Fig. 3.

Therefore, for practical purposes, there is no discernable effect in the far wake evolution. This finding is believed to be consistent with the conceptual and theoretical narrative that a retrofitted winglet is to produce a concentrated local change in the spanwise loading, and a localized change is not likely to affect the vortex system[12]. For departure, the larger difference seen in Fig. 2 is likely due to the fewer data points involved in the WL cases relative to the NWL cases.

Closing Remarks

A case study involving the wake decay evolution of winglet vs non-winglet variants of the B752 has been made. The results suggest that retrofitted B752 winglets have no discernable influence on the wake of this specific aircraft. These results also imply that the vortex spacing is not meaningfully affected by the addition of winglets on the B752, at least at high lift configuration when the wings tend to be more loaded inboard. It should be kept in mind that the results presented herein are specific to B752 and might not be completely extendable to other airframes or wingtip devices without further case studies. However, it is reasonable to consider that unless other wingtip devices alter the wing loading distribution or reduce induced drag much more significantly than those reported in Refs 10-11, the initial circulation change associated with wingtip devices is likely to be at the measurement noise level, and the winglet extension due to retrofit does not alter the vortex spacing in an operationally significant way.

However, if the assumption that the percentage of wingspan increases due to wingtip device is taken to be the same as vortex spacing increase, it would lead to a conservative estimate of the wake strength evolution, should a conservative estimate be sought.

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