Experimental Measurements of Passenger Ride Quality During Aircraft Wake Surfing

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The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center completed a series of research flights to better understand the challenges of aircraft wake surfing using civilian airplanes and commercial avionics. Airlines and air cargo carriers have identified uncertainty about increased passenger/crew discomfort due to noise and vibrations as a potential obstacle to the widespread adoption of aircraft wake surfing. To measure the effects of wake surfing on passenger ride quality, NASA instrumented a business jet with cabin noise and vibration sensors. The airplane was then flown under control of an experimental autopilot at multiple locations within the wake of a similar airplane. This paper presents a summary of the measurements collected on those flights, an assessment of passenger discomfort correlated with wake surfing performance benefits, and qualitative evaluations collected from passengers aboard during the research flights.

I. Nomenclature

ADS-B	= Automatic Dependent Surveillance - Broadcast
FS	= fuselage station
Fwd	= forward
GPS	= global positioning system
ISO	= International Organization for Standardization
Mid	= middle
MSDV	= motion sickness dose value
NASA	= National Aeronautics and Space Administration
PSD	= power spectrum density
RMS	= root-mean-squared
UTC	= Universal Time Coordinated
VDV	= Vibration Dose Value

II. Introduction

In 2017, the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California) conducted a series of flight experiments to explore the feasibility of automated aircraft wake surfing at extended trail distances while using civilian aircraft and commercial avionics. The tests were performed at a trail distance of 4,000 ft, or approximately 50 wingspans. The time-in-trail at this distance was just under six seconds. Wake surfing is a method for extracting energy from the trailing wingtip vortices of another airplane (Ref [1]). The energy is extracted by placing the wingtip of the trail airplane into the upwash portion of the vortex. The vortex upwash reduces the induced drag (drag due to lift) of the wing. Wake surfing has been demonstrated in flight using straight-wing propeller-driven aircraft (Refs. [2, 3]), jet fighter aircraft (Refs. [4, 5]), and large military transport aircraft (Refs. [6, 7]).

The recent NASA flight research measured the effects of wake surfing on passenger ride quality and correlated those effects with performance benefits, specifically reduction in fuel flow. Previously, Allen (Ref. [8]) evaluated the potential nausea effects of string instabilities in large formations of aircraft. Bizinos and Redelinghuys (Ref. [9]) predicted a significant increase in passenger discomfort for two B747s in wake surfing operations. Conversely, Okolo,

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Dogan, and Blake (Ref. [10]) predicted no increase in discomfort due to wake surfing for a formation of two KC-135 tankers. Both of these analytical studies assessed passenger ride quality using the ISO-2631 (Ref. [11]) standard for the evaluation of human exposure to whole-body vibration. Bieniawski (Ref. [7]) reported a slight degradation in ride quality associated with C-17 wake surfing based on in-flight measurements, using a NASA metric developed by Leatherwood (Refs. [12, 13]) that produces a total discomfort measure based on noise and vibration levels.

This paper presents both quantitative and qualitative assessments of ride quality degradation recorded on board a business jet aircraft while wake surfing. Quantitative measures consist of three-axis vibrations recorded on the seat rails and in the aft baggage compartment of both aircraft in the formation. Noise levels were also recorded in the cabin of the trail airplane. These measurements are correlated with wake-induced changes in fuel flow, and with qualitative ratings and descriptive evaluations provided by the flight crew and passengers.

Section III presents a description of the flight experiment, including the two aircraft, research instrumentation, test methodology, and a summary of the completed test points presented in this paper. Section IV presents passenger ride quality sensor data gathered during wake surfing test points. Section V presents an analysis of the gathered sensor data using three commonly used passenger ride quality metrics. Section VI summarizes the results of qualitative surveys completed by members of the test team who were aboard the trail airplane during the wake surfing flights. Finally, Section VII discusses the impacts of wake surfing on passenger ride quality. An examination of the physical causes of ride quality degradation during wake surfing flight is outside the scope of this paper, and is not addressed.

III. Flight Experiment Description

In 2017, NASA flew a series of four research flights with a Gulfstream C-20A airplane (Gulfstream Aerospace, Savannah, Georgia) performing wake surfing behind a Gulfstream III (G-III). The trail airplane was equipped with an experimental programmable autopilot that controlled the lateral and vertical position of the airplane relative to an estimate of the location of the wake of the lead airplane. Along-track position to the lead airplane was manually controlled by pilot throttle inputs. Tablet computers mounted on the pilot's and co-pilot's yokes displayed throttle command cues, along-track command, range and error, and the predicted wake location. See Reynolds (Ref. [14]) for a detailed description of the pilot displays used for this flight experiment and Hanson (Ref. [15]) for more details regarding the wake surfing performance measurements and analysis.

A. Aircraft Descriptions

The C-20A airplane is a military variant of the G-III airplane. The relevant differences between the lead airplane and the trail airplane, shown in a non-wake-surfing flight formation in Fig. 1, are the cabin layout and external configuration.

The G-III lead airplane interior and exterior were typical business jet configuration. The C-20A trail airplane has been modified to carry an experimental sensor pod on the centerline below the wing. While the pod was removed for the wake surfing research flights, the pylon mount remained installed and increased fuel consumption when compared to the lead airplane at similar flight conditions and gross weights. The interior cabin of the C-20A airplane was in an experimental configuration, with multiple equipment racks located on both the left and right sides of the cabin, as shown in Fig. 2.

Fig. 1. NASA C-20A (white/blue) and G-III (all white) aircraft in close formation flight.

Fig. 2. Tail aircraft cabin equipment racks and researchers.

B. Test Instrumentation

Avionics bus data were collected for the trail airplane during the test flights, including altitude, airspeed, winds, position and velocity, control surface positions, pitch and roll rate, and Euler angles. Airspeed, winds, position and velocity, and roll angle were also recorded from the avionics bus of the lead airplane. Both aircraft were equipped with independent global positioning system (GPS) receivers for making post-flight, high-precision calculations of relative position and velocity. Accelerometers were installed on the seat rails of both airplanes to measure vibration levels perceptible to the passengers. Ride quality sensor locations on the trail airplane are shown in Fig. 3, and an example accelerometer installation is shown in Fig. 4.

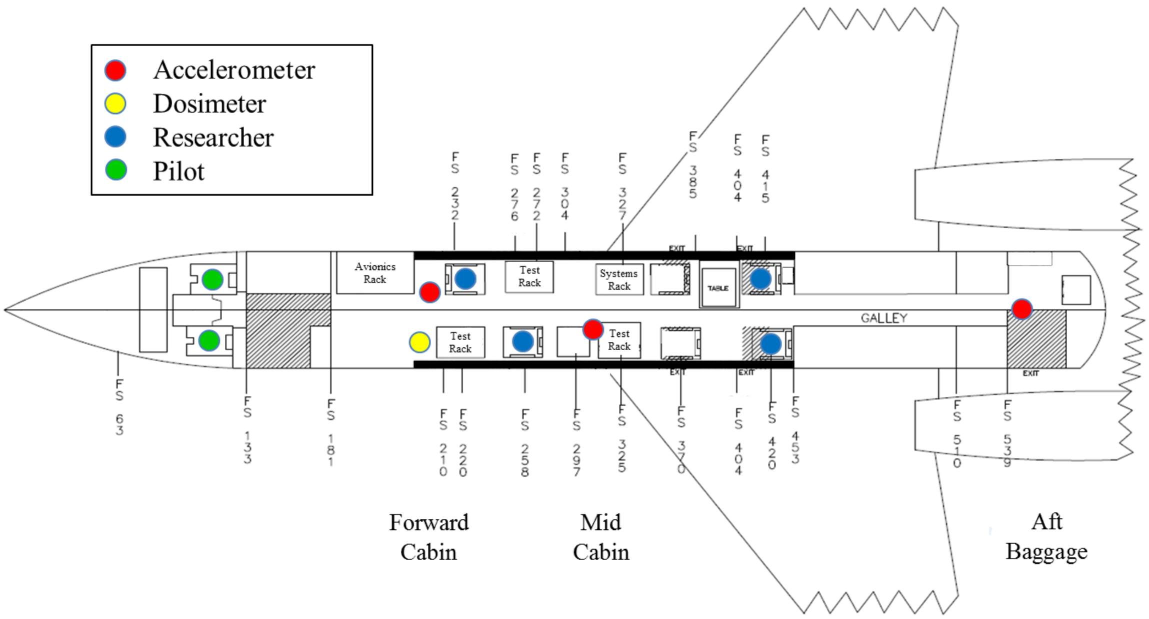

Fig. 3. Cabin layout of the Gulfstream C-20A trail airplane.

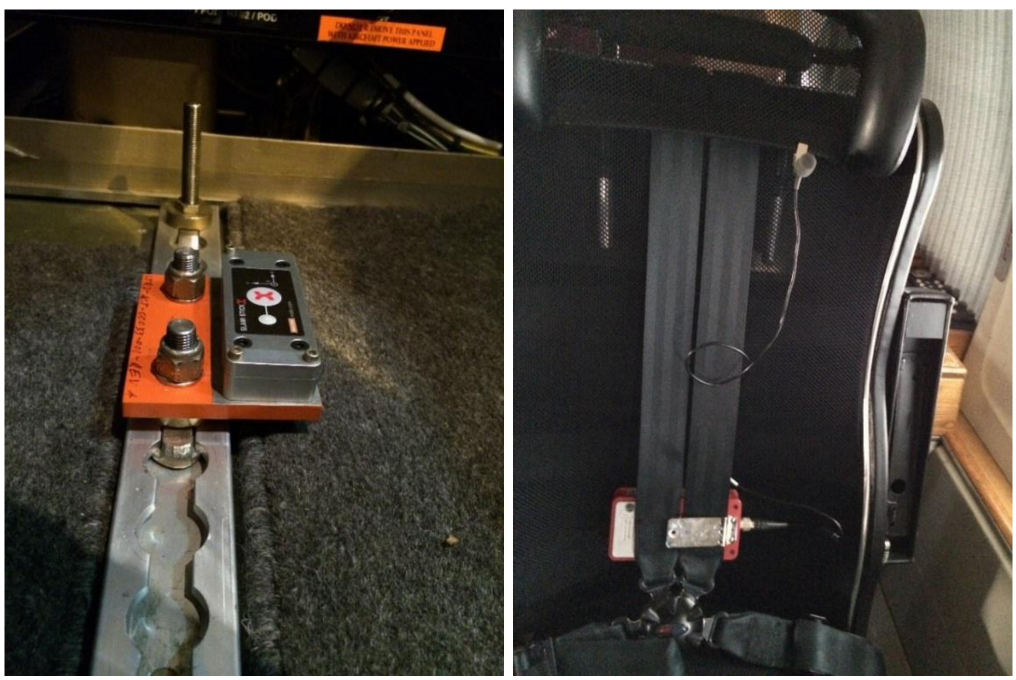

Fig. 4. Installation of a seat rail accelerometer and dosimeter.

Seat rail placement is the recommended procedure for measuring vibration to assess passenger discomfort (Ref. [16]) since measurements made at a rigid surface can be corrected for seat cushion transmissibility effects (Refs. 17, 11]). Additional accelerometers were attached to the aircraft structure on the ceiling in the aft baggage compartment of each airplane. The accelerometers used are small, lightweight, self-contained sensor packages that include separate tri-axial accelerometers for high-frequency and low-frequency responses, as well as pressure and temperature sensors, and onboard time-stamped data logging. The mid-cabin seat rail and aft baggage compartment accelerometers were located at nearly identical fuselage stations between the two aircraft for purposes of comparison. Table 1 presents the accelerometer specifications.

Table 1. Accelerometer specifications.

Airplane	Location	High-frequency range/resolution	Low-frequency range/resolution
Lead	Mid-cabin seat rail, right	25 g / 0.0008 g	16 g / 0.004 g
	aft baggage compartment	100 g / 0.003 g	16 g / 0.004 g
Trail	Forward seat rail, right	100 g / 0.003 g	16 g / 0.004 g
	mid-cabin seat rail, left	25 g / 0.0008 g	16 g / 0.004 g
	aft baggage compartment	25 g / 0.0008 g	16 g / 0.004 g

A noise dosimeter recorded sound levels in the cabin of the trail airplane during wake surfing test points. An image of the dosimeter installation is shown in Fig. 4. The dosimeter measures sounds in a frequency band of 100 Hz to 5 KHz, at levels between 40 dB and 140 dB. The dosimeter is battery-powered and self-records time-averaged noise levels once per minute. The dosimeter microphone was placed at ear level on a cabin seat on the left-hand side of the airplane, across the aisle from the forward cabin seat rail accelerometer.

Direct measurements of fuel flow were not available for onboard recording without breaking into the production aircraft systems, so a small, portable video camera with internal recording was installed on the cockpit console with a view of the left and right engine fuel flow gauges. Just prior to takeoff, the internal clock on the camera was synchronized with a GPS time source. Recording start and stop times were also noted for post-flight correlation of the video with the ride quality sensors and other onboard data sources. At various times during each test point, pilot call-outs of fuel quantities from both airplanes were recorded by hand. The pilots' fuel quantity readings have a resolution of 100 lb.

C. Test Methodology

All wake surfing test points were flown at a Mach number of 0.75 and an altitude of 35,000 ft in the United States Navy W-291 test range over the Pacific Ocean off the coast of Southern California. This flight condition was chosen as approaching cruise conditions while still providing sufficient structural margin on winglet and tail loads in the event of an inadvertent wake crossing. Three-axis steering cues were provided to the trail airplane test pilot to maneuver into the desired position relative to the wake of the lead airplane prior to engaging the research system. The research autopilot was engaged approximately 4000 ft aft of the lead airplane and outside of the predicted region of wake effects. The in-trail distance of 4000 ft was chosen for all of the wake surfing tests because it equates to approximately 50 wingspans, which is at the larger end of the presumed usable range of extended formation flight for wake surfing (Ref. [18]).

Following engagement, the pilot of the trail airplane maintained the desired along-track spacing to the lead airplane through manual throttle adjustments, based on position cues from the research system displayed on a tablet computer mounted to the control yoke. The research autopilot maintained the desired cross-track and vertical position based on own-ship data and ADS-B information transmitted from the lead airplane. The experiment test conductor entered new position commands to the research autopilot by way of a laptop computer. As shown in Fig. 5, wake surfing flight test points generally followed the process of:

1) an initial tare point,
2) systematic wake ingress,
3) stabilized wake surfing for performance and ride quality characterization, and
4) a post-test tare point.

The locations depicted in Fig. 5 represent the centerline locations of the aircraft and wake, not the wingtip or vortex core. During tare points, the team gathered a minimum of three minutes of data while stabilized outside the wake area of influence. Wake ingress was initiated when the test conductor commanded the trail airplane to a position within the wake effects and allowed the dynamics to stabilize. New position commands were subsequently chosen to incrementally move deeper into the wake. Once the experimental autopilot's steady-state roll trim surpassed a pre-specified criteria, or a significant change in ride quality was reported by the researchers in the cabin of the trail airplane, the current position command was maintained while wake surfing performance and ride quality measurements were collected. Wake surfing dwell times were a minimum of five minutes. Following the wake surfing points, the trail airplane was commanded out of the wake so that a post-test tare point could be completed.

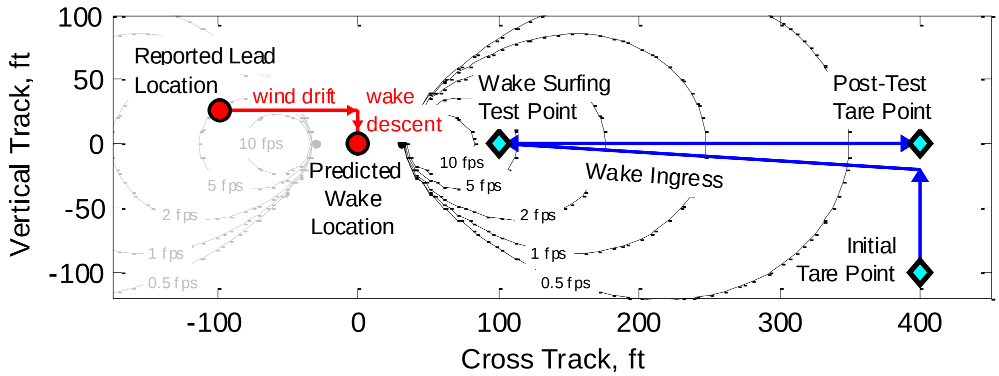

Fig. 5. Vortex upwash map with wake prediction and flight test points.

D. Summary of Completed Test Points and Test Points Presented in this Paper

The first three wake surfing flights were focused on developing test techniques, adjusting gains to improve stability and system tracking performance in wake effects, refining the pilot throttle cue display, and gathering measurements to characterize the wake field based on the trim state of the trail airplane at different locations within the wake. The purpose of the final flight was to gather wake surfing performance and ride quality data. In all, the project completed 17 tare points, 30 wake ingress sequences, and 10 stabilized wake surfing points. There were also 10 inadvertent wake crossings during the four wake surfing flights.

This paper discusses the passenger ride quality effects measured during the two test points on the final flight - hereafter referred to as Test Point 2 and Test Point 7 - having the largest performance benefits, as well as briefly touching on passenger response to wake crossings. Table 2 lists the test points and maneuvers included in the analysis presented in this paper.

Table 2. Description of test points and maneuvers included in the analysis presented in this paper.

Test point	Maneuver	Turbulence reported by lead aircraft	Included in analysis Trail	Included in analysis Lead
0	tare point	light chop (weak)	x	
1	tare point	light chop (strong)	x	
2	tare point	calm air	x	
	wake ingress	calm air	x	x
	wake surfing	calm air	x	x
7	tare point	calm air	x	
	wake ingress	calm air	x	x
	wake surfing	calm air	x	x

At the beginning of the flight, during Test Point 0 and Test Point 1, two tare points were completed under what the pilots described as “light chop” conditions. Trail airplane data from these two maneuvers were analyzed and are included in this paper as points of comparison to passenger ride quality in wake effects. The tare points at the beginning of Test Point 2 and Test Point 7 showed no signs of turbulence. An analysis of the ride quality of the trail airplane during these tare points provides a “calm air” comparison. Measurements from both aircraft during Test Point 2 and Test Point 7 were analyzed and are presented in this paper to illustrate the concurrent differences in ride quality between an airplane in wake effects and an airplane in undisturbed air.

IV. Ride Quality Sensor Measurements

Measurements of seat rail vibration and cabin noise are presented below. Ride quality sensor recording was activated shortly before the first test point of the flight and remained continuously active until after the final test point was complete. The internal clock of each sensor was synchronized to UTC time on the day prior to each flight, and recording start and stop UTC times were noted by hand to aid in post-flight correction of clock drift and with correlation to other onboard data sources. All accelerometers and the dosimeter were calibrated prior to the flight experiment.

A. Seat Rail Vibration

Accelerometers mounted on the seat rails of both the lead and the trail airplanes recorded tri-axial vibrations during wake surfing at multiple locations within the wake field of influence. Figure 6 shows the measurements recorded during two wake surfing test sequences. A tare point was completed at the beginning of the sequence to gather baseline data outside the wake area of influence. The tare point was followed by a series of cross-track and vertical step commands into the wake flow field. Following the wake ingress, an extended stabilized wake surfing test point was completed to gather performance and ride quality data.

From the raw acceleration measurements shown in Fig. 6, it is apparent that the trail airplane began to experience increased vibrations during the wake surfing portion of the test point as compared to the tare and wake ingress portions. The strongest vibrations appear in the vertical axes, and are more pronounced at the mid-point of the cabin than at either the forward cabin or the aft baggage compartment. In fact, there appears to be very little change in vibration at the aft location.

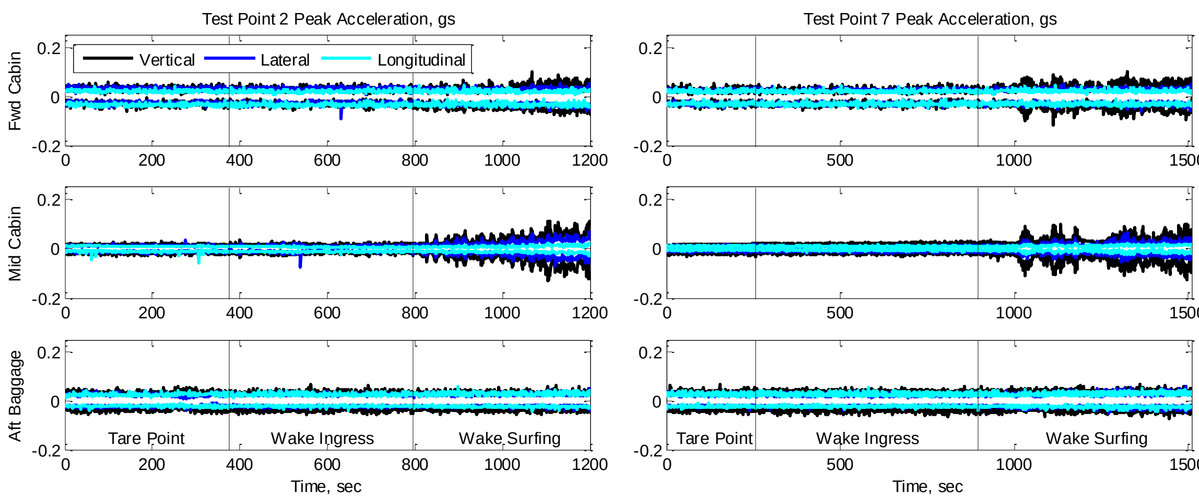

Fig. 6. Cabin peak accelerations during two wake surfing test points.

The power spectrum density (PSD) of the vibrations recorded during the stabilized wake surfing portions of Test Point 2 and Test Point 7 are shown in Fig. 7. Also shown are regions bounded by the power spectra for tare points (out of the wake influence) that were completed on the same flight: two in calm air and two in light turbulence. At the mid-cabin and aft-baggage locations, the power spectra are also shown for the lead airplane during the wake surfing test points. As in the peak acceleration plots, the PSDs show increased vibration at the forward and mid-cabin locations during the wake surfing test point and little change at the aft location, as compared to the calm air tare points.

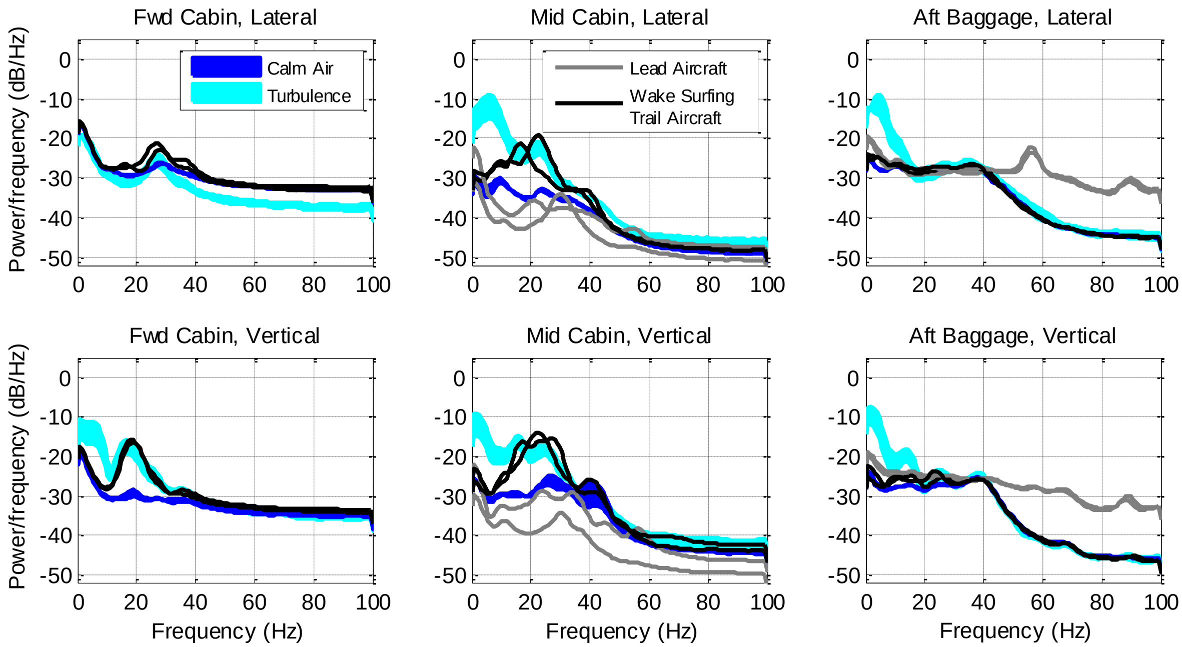

Fig. 7. Cabin vibration during two wake surfing test points compared with flight through calm air and non-wake turbulence.

At the forward cabin location, the peak lateral wake-induced vibrations occur in the range of 26 Hz to 28 Hz, while the peak vertical vibrations are at 19 Hz. The vibration characteristics observed during wake surfing are similar to those of the turbulent tare points, with the exception of stronger low-frequency content in the vertical axis during the turbulent cases.

The mid-cabin accelerometer measurements show an increase in vibration levels during wake surfing, both when compared to the accelerations recorded on the lead airplane during the same time period and when compared to the trail airplane vibrations during the smooth air tare points. Although the lead airplane PSD is only shown for the wake surfing portion of the test, those power spectra are nearly identical to the calm air tare points, indicating that the increased vibrations measured on the trail airplane are not a result of clear-air turbulence.

As with the forward cabin readings, the wake-induced vibrations on the trail airplane at the mid-cabin location are similar to the measurements taken during the two turbulent tare points, except that the turbulent points contain more low-frequency energy. In contrast to the forward cabin measurements, the wake-induced vibrations occur across a wider frequency range: 16 Hz to 23 Hz in the lateral axis and 17 Hz to 27 Hz in the vertical axis.

At the aft baggage compartment location, measured accelerations during the wake surfing test points are indistinguishable from those of the calm air tare points. The accelerometer at that location did measure increased vibration during the turbulent tare points, confirming that wake surfing vibrations would have been recorded had they been present.

To illustrate the relationship between wake-induced vibrations in the cabin of the trail airplane and wake-induced performance benefits, the root-mean-squared (RMS) acceleration measurements are plotted against the estimated reduction in fuel flow in Fig. 8. Each data point in the figure represents a one-second time-averaged value. Aft baggage compartment results are not shown because there were no measured wake vibrations at that location. Other than lateral acceleration at the forward cabin location, there is clearly an increase in cabin vibrations at higher levels of wake-induced fuel flow reductions. The effect is strongest in the vertical axis, and at the mid-cabin location.

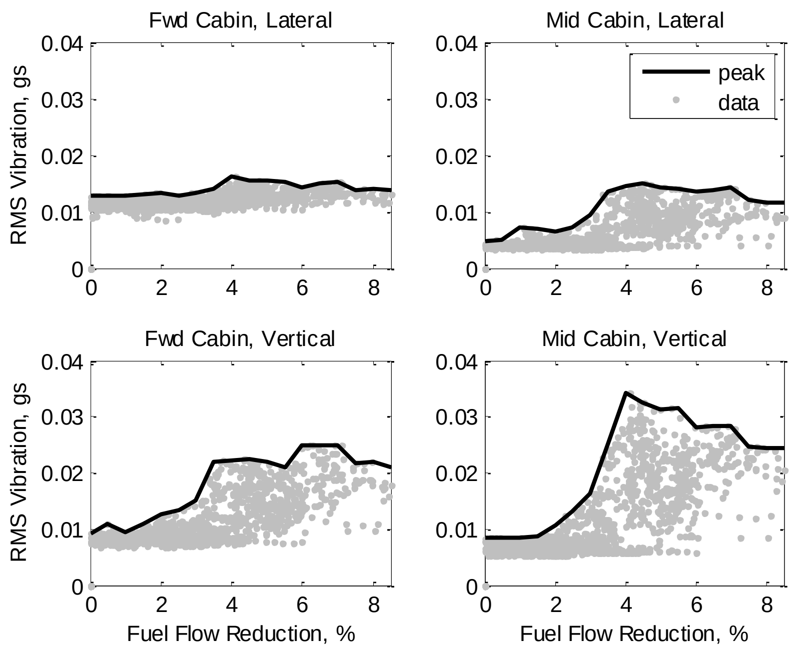

Fig. 8. Cabin seat rail acceleration versus fuel flow reduction due to wake surfing.

B. Cabin Noise

Sound levels measured in the cabin of the trail airplane during Test Point 2 and Test Point 7 are shown in Fig. 9, plotted against time and also percent fuel flow reduction. Sound levels were averaged over one-minute intervals before being recorded by the dosimeter. The average ambient cabin noise level of the C-20A airplane was between 81 and 82 dB. As a comparative example, Ozcan and Nemlioglu (Ref. [19]) measured continuous in-cabin noise levels between 75 and 78.5 dB for an Airbus A321 airplane (Airbus Group SE, Leiden, The Netherlands) in cruise flight. A slight increase of 1-2 dB was measured during the wake surfing portion of the test points. The wake ingress sequences were not significantly noisier than the calm air tare points.

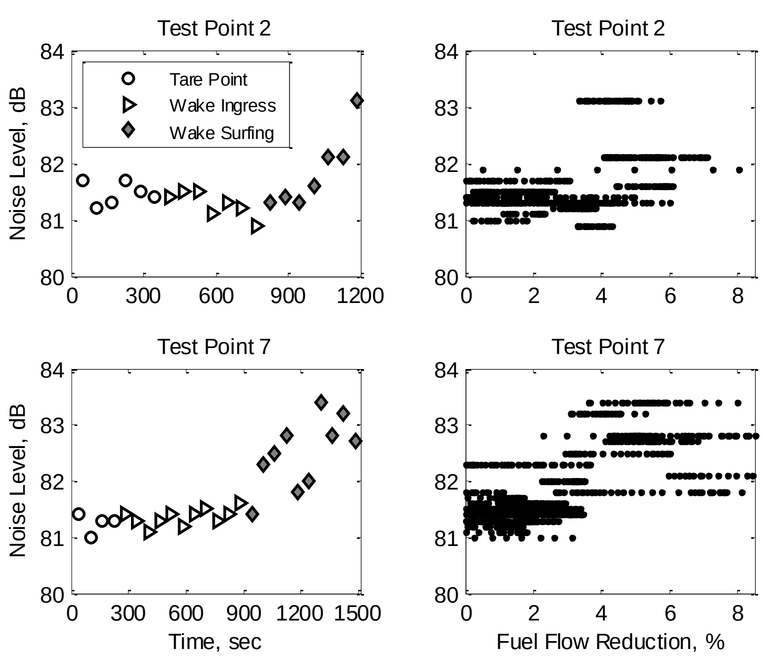

Fig. 9. Cabin noise during two wake surfing test points.

V. Ride Quality Metric Results

In order to evaluate the effects of wake surfing on passenger ride quality, existing metrics for mapping multi-axis seat accelerations to passenger discomfort were applied to the measurements gathered during the flight experiment. Two metrics were used to predict passenger sensitivity to the flight-measured high-frequency vibrations, and a third metric predicted the likelihood of passenger motion sickness due to low-frequency oscillations.

A. NASA Discomfort Metric

In the late 1970s, NASA researchers developed a passenger discomfort metric using empirical data collected during a series of human subject studies in a motion aircraft simulator (Ref. [12]). The metric is a single numerical rating that relates lateral, vertical, and roll accelerations, combined with cabin noise levels, to a percentage of passengers that will find them uncomfortable.

The wake surfing experiment did not record roll acceleration, so that component is not included in this analysis. Additionally, the high ambient cabin noise in the trail airplane tended to dominate the discomfort metric calculations, obscuring any changes attributable to wake effects. Consequently, the metrics presented in this section are based on a combination of the measured lateral and vertical accelerations only.

As part of calculating the NASA discomfort metric, the measured vibrations are frequency-weighted to account for the frequency-dependent sensitivity of the human body. The metric was developed for cabin vibrations in the range of 1 Hz to 30 Hz in the vertical axis, and 1 Hz to 10 Hz in the lateral axis. As discussed above, the peak lateral vibrations observed during the wake surfing tests occurred at frequencies as high as 28 Hz. The lateral axis frequency weightings proposed by Leatherwood (Ref. [12]) were modified for this analysis by applying the 10-Hz weighting to all frequencies above 10 Hz. It should also be noted that the transmissibility effects of seat cushions were not included.

Using the Leatherwood (Ref. [12]) method under the assumptions discussed above, the NASA discomfort metric was calculated at one-second intervals for the forward and mid-cabin locations. The peak discomfort ratings are plotted against the estimated wake ingress and wake surfing fuel flow reduction in half-percent increments in Fig. 10. Although initially, at lower levels of wake benefit, the NASA metric predicts increased passenger discomfort with increasing fuel savings, this trend eventually levels off and the discomfort rating remains relatively steady or even decreases slightly.

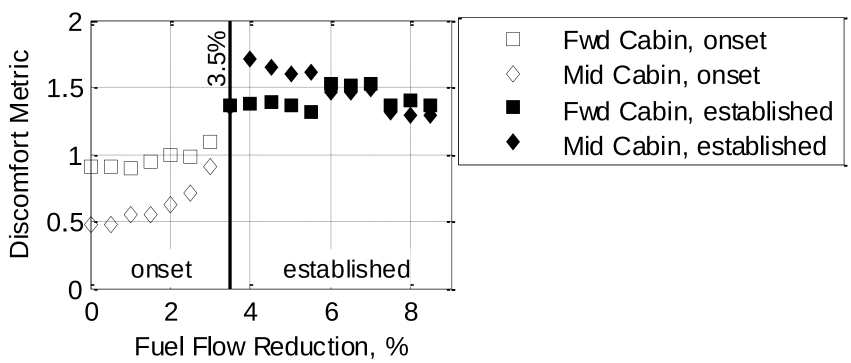

Fig. 10. Wake-affected passenger discomfort metric versus fuel flow reduction.

An arbitrary threshold was established at 3.5-percent fuel flow reduction, above which both cabin locations are predicted to have a passenger discomfort rating above 1, meaning 50 percent of passengers are predicted to rate the experience as "uncomfortable." The onset of wake-induced passenger discomfort occurred between 0- and 3.5-percent fuel savings. Above this level of savings, the wake effects on passenger ride quality appeared to be fully established.

Leatherwood (Ref. [12]) gives a criteria function that correlates the NASA discomfort metric to a percentage of passengers who might find the experience uncomfortable. Figure 11 relates the predicted percentages at the forward and mid-cabin locations for flight in calm air to the peak values in wake effects. Discomfort regions bounded by predictions for the two turbulent tare points are shown for comparison, as is the level of discomfort predicted for the mid-cabin location of the lead airplane during the wake surfing test points.

The results shown in Fig. 11 predict that just over 70 percent of passengers might find wake surfing to be uncomfortable at the forward cabin location, about the same as the upper bound of predictions for light turbulence. The prediction for calm air at the same cabin location is just under 50 percent. The calm air number seems unusually high for a business jet and may be an indication that the metric is over-predicting passenger discomfort for this particular configuration.

The mid-cabin location appears to have a more benign ride quality state outside of wake effects than the forward cabin, with a calm air discomfort prediction of 29 percent, close to the 24 percent of the lead airplane. The peak prediction of 80 percent, however, is higher than at the forward cabin location although still within the range of predictions for light turbulence.

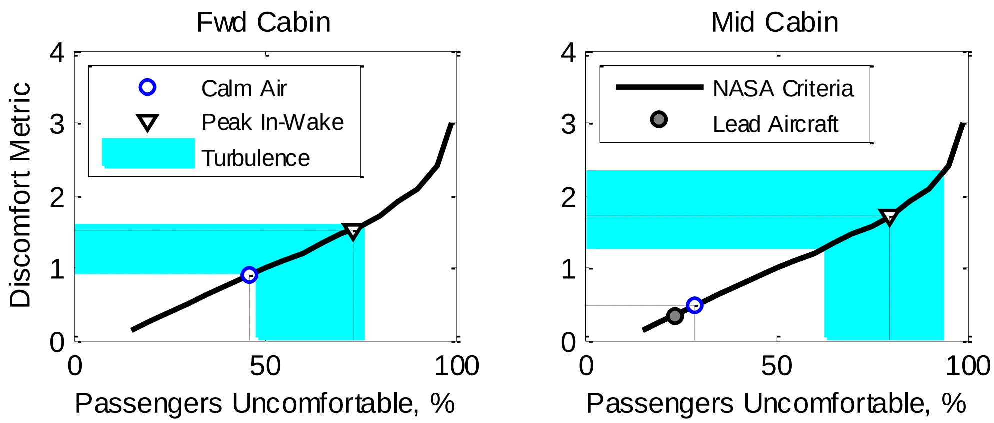

Fig. 11. Passenger discomfort during wake surfing, NASA metric.

B. ISO-2631 Discomfort Metric

Another passenger discomfort metric is found in ISO-2631 (Ref. [11]). The ISO metric combines the frequency-weighted RMS of measured lateral and vertical accelerations into a single discomfort measure, called the Vibration Dose Value (VDV). Although the VDV also supports the use of longitudinal measurements, those were small for the wake surfing test points and not included in this analysis. The ISO-2631 standard provides guidelines for relating VDV to qualitative human ratings. These ratings are assumed to increase with the one-fourth-power of exposure time. Figure 12 shows a comparison of the wake surfing VDV discomfort metric at all three cabin locations over 10 hours to those of flight in calm air and turbulence for the experiment test points.

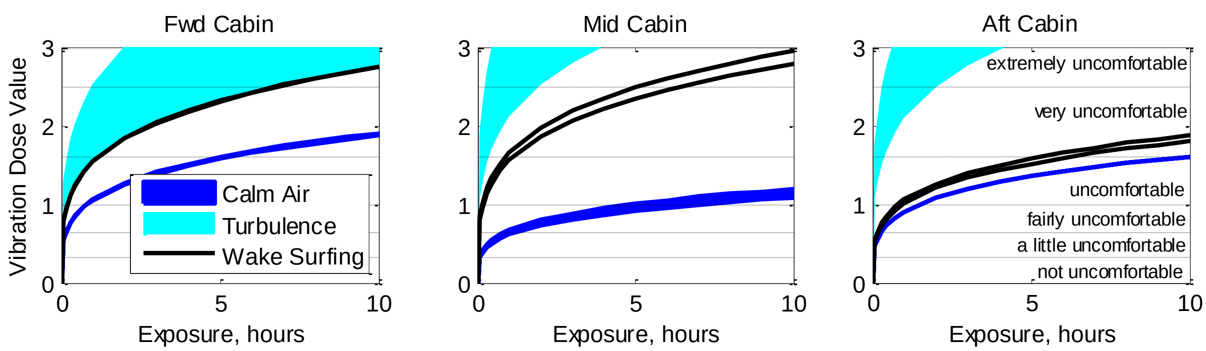

Fig. 12. Passenger discomfort during wake surfing, ISO metric.

At the forward cabin location, the ride quality measures during the two wake surfing test points are nearly identical and at the lower range of those for flight through turbulence. The predicted discomfort level very quickly reaches the "uncomfortable" region, and passes into "very uncomfortable" after about an hour. Finally, for exposure times greater than seven hours the discomfort due to wake surfing is solidly in the "extremely uncomfortable" region. It should be noted that the VDV during flight outside the vortex reaches the "very uncomfortable" level after about five hours, which seems unlikely for a business jet aircraft. This suggests the metric may over-predict passenger discomfort.

The magnitude of the mid-cabin wake surfing discomfort prediction is very similar to that of the forward cabin, while the calm air VDV is more benign and the turbulent VDV is more severe. These results predict that the effects of wake surfing are less uncomfortable than those of flight through turbulence at this cabin location, although still worse than flight through calm air. As expected from the raw acceleration measurements and their PSDs, the aft baggage compartment shows almost no ride quality degradation due to wake surfing.

C. ISO-2631 Motion Sickness Metric

The ISO-2631 standard also gives a metric for predicting passenger nausea due to continuous low-frequency motion in the vertical axis. A motion sickness dose value (MSDV) is calculated as the frequency-weighted RMS of the acceleration measurement multiplied by the square root of the exposure duration. An estimate of the number of passengers who may become susceptible to nausea and vomiting during the exposure time is found by multiplying the MSDV by a constant. The constant value used in this analysis, as recommended by ISO-2631, is one-third. Figure 13 shows the predicted motion sickness rate for the two wake surfing test points compared to values for flight through calm air and through turbulence.

For this analysis, measurements from the low-frequency accelerometers were used in place of the high-frequency values used for the discomfort metrics to better capture low-frequency content. All three cabin locations have very similar wake surfing motion sickness curves, and are only slightly higher than the calm air predictions. In contrast, the turbulence motion sickness rate is approximately four times higher, likely due to the increased low-frequency content recorded during the turbulent tare points (refer to Fig. 7).

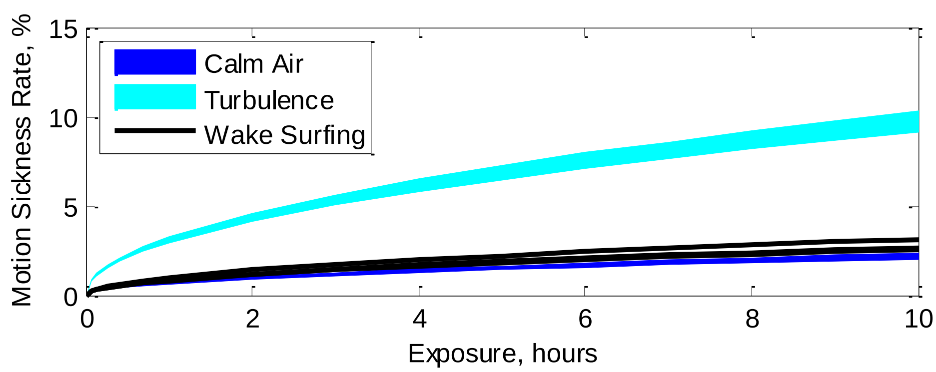

Fig. 13. Passenger nausea during wake surfing, ISO metric.

VI. Passenger Qualitative Survey Results

In order to better understand the ride quality sensor data gathered during the wake surfing test flights, qualitative evaluations of the impact of wake surfing on passenger comfort levels were obtained through surveys of individuals aboard the trail aircraft. Each test subject was asked to complete a pre-flight questionnaire to record their general feelings about flying, their recent level of passenger flight activity, the relative importance of various contributing factors to their personal assessment of comfort, and history of motion sickness. Following the flight campaign, each subject was asked to complete a questionnaire to evaluate both steady-state wake surfing and inadvertent wake crossings. Both questionnaires were modified versions of the ground-based and in-flight questionnaires developed by Richards and Jacobson (Ref. [20]) to assess airline passenger comfort.

A. Survey Participants

Ten individuals were included in the survey, all of whom were aboard the trail airplane during one or more test flights. The pool of respondents comprises three categories: 1) pilots, 2) project engineers, and 3) non-project personnel. All surveyed individuals are atypical air travelers in that they all reported a high number of flights over the previous two years, all work in the aerospace sector, and all but one expressed feelings of enjoyment related to aircraft flight. All respondents wore headsets for communication, and one respondent was seated in an aft-facing seat.

The two pilot respondents are unique compared to the other members of the flight team due to their higher level of flight training and experience, as well as their duties and location during the flights. Both pilot and co-pilot were positioned in the cockpit during all test points and reported having experienced numerous wake encounters during their careers. The pilot-in-command was tasked with operation of the throttles to maintain along-track spacing to the lead airplane using an experimental display, while the co-pilot was responsible for radio communications, safety monitoring of the experiment, and all other aircraft operations.

The five project engineers surveyed were involved in the design and implementation of the system under test. While each provided honest responses to the survey questions, their unique insight into the performance and expected behavior of the experimental system should be taken into consideration. Duties for the project engineers during the test flights include system control, data observation and analysis, documentation of events, and overall mission coordination. Four project engineers were aboard the trail aircraft on each flight, located in the cabin of the aircraft.

Three non-project individuals also participated in the test flights. Two of these are operations/systems engineers located in the main cabin, only one on a given flight. These individuals' role was to monitor instrumentation, and to coordinate activity in the cabin in the event of an emergency. The third non-project individual is a videographer, who was present on one flight and split time between a cabin seat and the cockpit jump seat.

B. Pre-Flight Questionnaire Results

All of the survey participants reported extensive flight activity over the two years prior to and including the experiment flights. Eight of the respondents reported participating in 10 or more NASA research or operational flights, while seven reported taking 10 or more commercial flights in the same time period. Additionally, five of the respondents had flown in a small private aircraft at least once during the reporting period.

All but one of the respondents reported either enjoying or strongly enjoying flying, with the remaining individual reporting neutral feelings on the subject. The majority described both up/down motion and rolling motion to be very important to their assessment of passenger comfort, while all but three indicated that noise plays a somewhat less important role.

C. Wake Surfing Survey Results

While each stabilized wake surfing test point lasted for fewer than 10 minutes, and the total time spent in wake effects on the final experiment flight was less than two hours, the respondents were asked to extrapolate their experience to a typical four- to five-hour commercial flight. The average response of all participants to the ride quality of sustained wake surfing was between neutral and comfortable. Only one respondent characterized the feeling as uncomfortable. A small minority estimated that they would find writing or sleeping difficult while experiencing the motions associated with wake surfing. None reported any hesitation at the idea of taking a commercial flight that might include a similar ride quality.

In comments accompanying the survey, the most common comparison of the ride quality of wake surfing was with flight through light turbulence. In several cases the effect was described as "rumbling" and also compared with driving along a washboarded road. Two respondents in the main cabin of the airplane reported an auditory component in addition to a physical sensation. Finally, several respondents indicated that although they were not bothered by the ride quality of wake surfing, they felt that members of the flying public might find it objectionable. One participant suggested that some people could find the sight of contrails outside their windows to be unsettling (see Fig. 14).

Fig. 14. Contrails visible outside cabin window during wake ingress.

D. Wake Crossing Survey Results

On multiple occasions during each flight, the trail airplane inadvertently passed through the wake vortex of the lead airplane. These events were preceded by commanded changes from a stable position in the wake to one that could not be maintained, variations in winds or navigation data, or unexpected maneuvers by the lead airplane. With the exception of one non-project individual, wake crossings were rated more severely by the survey group than wake surfing.

All but one of the remaining responses characterized wake crossings as uncomfortable or very uncomfortable, and all described the activities of reading, writing, and sleeping to be difficult or impossible during a wake crossing. Half of the respondents indicated that experiencing a crossing during wake surfing as a passenger on a commercial flight would make them less likely to take another flight during which a similar event was a possibility.

VII. Discussion

The ride quality sensor measurements, passenger discomfort metric predictions, and qualitative passenger evaluations are discussed below. Recommendations for further work are also given.

A. Sensor Measurements

Measureable increases in seat rail vibration and cabin noise onboard the trail airplane were recorded during the wake ingress and wake surfing portions of the flight tests. The frequency and magnitude of the wake-induced vibrations changed with the measurement location in the airplane cabin, with the largest magnitude of vibration observed at the mid-cabin location. The strongest vibrations were recorded during flight in the strongest portion of the wake, equivalent to fuel flow reductions of 3.5 percent and greater. Above this level there was no direct correlation between sensed vibrations and the degree of wake surfing performance benefits. A slight increase in cabin noise was also recorded during wake surfing.

Vibrations were also recorded at two locations in the cabin of the lead airplane during all test points. These sensors recorded similar responses to the trail airplane during flight in atmospheric turbulence, but showed no increase in vibrations during the wake surfing test points. Under the assumption that both airplanes would encounter similar clear-air turbulence effects while flying through the same air mass within six seconds of each other, these results confirm that the vibrations recorded on the trail airplane during flight in the wake were a result of the presence of the wake and not atmospheric turbulence.

B. Passenger Discomfort Metrics

Two passenger discomfort metrics were applied to the data gathered from the NASA wake surfing flight experiments. In the interest of maintaining broad applicability, seat cushion transmissibility effects were not taken into account in the sensor installation or the data analysis. Measurements were taken at the seat rails, which is the recommended approach for the NASA metric and is an acceptable, although not the preferred, approach for the ISO metric.

Both metrics predict an increase in passenger discomfort due to wake surfing when compared to flight through calm air. Both discomfort metrics also predict similar passenger responses to wake surfing and flight in light turbulence outside the wake. Tare points with two levels of "light chop" were analyzed to provide metric predictions for a range of passenger discomfort due to light turbulence. Discomfort levels predicted for the wake surfing test points are either below or within these turbulence regions. There were no wake surfing ride quality predictions that were worse than the most severe light turbulence point analyzed.

The low-frequency vertical motions of the trail airplane during wake surfing were evaluated using the ISO motion sickness metric. No appreciable increase in the likelihood of passenger motion sickness was found related to flight within the wake, and was significantly lower than predicted nausea rates for flight in non-wake turbulence. There were no airsickness events during any of the wake surfing experiment flights.

These ride quality metric predictions should be considered in terms of their general trends, but not their specific numerical values. The ride quality metrics applied in this paper are based on generalized tools and standards that have not been validated for this specific application, and may not accurately reflect actual passenger discomfort during commercial wake surfing operations. Additional research is necessary to develop and validate the tools required to accurately predict the impacts of wake surfing on passenger discomfort.

C. Qualitative Survey Responses

All of the members of the test team aboard the trail airplane described the ride quality during wake surfing to be noticeably different from flight in calm air outside the wake. While none of the surveyed individuals found wake surfing to be objectionable, it should be noted that the sample size is small and not representative of the general flying public. The consensus among the test team is that wake crossings are undesirable events and should be avoided for commercial passenger aircraft.

D. Recommendations for Future Work

A definitive explanation for the cabin vibrations encountered during wake surfing is unavailable and outside the scope of this paper. Theoretical modeling of aircraft wakes in the near far-field region (10-50 wingspans downstream) that includes wake dynamics and breakup/dissipation could help provide an understanding of the mechanisms responsible for wake surfing ride quality degradation.

It is likely that sensed vibrations and noise are specific to individual airframes, with factors such as the presence of winglets, the number and location of engines, and wing stiffness playing an important role in transmitting wake turbulence to passengers. Additional flight research with instrumented civilian transport aircraft and human subjects is required to better predict the noise and vibration impacts of wake surfing on passenger discomfort during commercial operations. The results presented in this paper should be used as a starting point to guide future research. Of particular interest is gathering additional data to determine whether reducing in-trail spacing would reduce sensed vibrations and passenger discomfort.

The integration of passenger ride quality sensor measurements with a performance optimization algorithm could provide a means to automatically balance wake surfing fuel savings with passenger discomfort. The development of robust methods to prevent wake crossings is also critical to passenger acceptance of routine wake surfing.

VIII. Conclusion

Passenger ride quality measurements were collected on both aircraft during wake surfing operations with a Gulfstream C-20A airplane (Gulfstream Aerospace, Savannah, Georgia) serving as the trail airplane behind a Gulfstream III (G-III) airplane. Lateral and vertical seat rail vibrations and cabin noise showed measureable increases associated with flight in the portions of the wake with the greatest levels of wake surfing benefits. Recorded seat rail vibration magnitude and frequency were found to vary with cabin location. These measurements were analyzed with three commonly used passenger ride quality metrics and compared to flight outside the wake in both calm air and atmospheric turbulence. Researchers aboard the trail airplane during the test flights generally rated the experience more favorably than the ride quality predictions, although they both assessed flight in the wake as similar to flight in light turbulence. Additional flight research with instrumented civilian transport airplanes and human test subjects is necessary to fully contextualize these results across a broad range of aircraft and flight conditions.

Acknowledgements

This work was performed under the NASA Transformative Tools and Technologies project, and the NASA Flight Demonstrations and Capabilities project. The Gulfstream C-20A test airplane is maintained and operated by the NASA Science Mission Directorate.

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