G-LOC Due to the Push-Pull Effect in a Fatal F-16 Mishap

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BACKGROUND: The risks associated with high positive G_z ($+G_z$) aerobatic flight, especially with respect to $+G_z$-induced loss of consciousness (G-LOC), are well known. Less appreciated is the effect of negative G_z ($-G_z$) flight on subsequent $+G_z$ maneuvers, known as the "push-pull effect." This is an example involving the loss of an F-16 and pilot that was caused by the push-pull effect.

CASE REPORT: The mishap pilot (MP) was killed during a training flight when his F-16 crashed without an ejection attempt. The MP, while transitioning from prolonged $-G_z$ flight to sustained $+G_z$ flight, maneuvered the mishap aircraft (MA) from -2.06 G_z to $+8.56$ G_z in less than 5 s. At this point, there were only minimal control inputs for 5 s, indicating the MP experienced transient incapacitation, most likely due to G-LOC or almost loss of consciousness (A-LOC). The MP's subsequent recovery attempt was interrupted by ground impact. The Accident Investigation Board (AIB) concluded the MP experienced G-LOC due to the push-pull effect.

DISCUSSION: Since this is not the first time the push-pull effect has resulted in G-LOC mishaps, the adverse effects of such maneuvers should continue to be emphasized during military physiological training, as well as during general aviation (GA) aerobatics training. Furthermore, A-LOC, instead of being considered a discrete phenomenon, may need to be included in a broader G-LOC definition that encompasses the entire continuum of G-LOC and A-LOC.

KEYWORDS: accident investigation board, anti-G straining maneuver (AGSM), A-LOC, baroreceptor reflex.

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Both military and general aviation (GA) pilots routinely fly high G_z aerobatics in airshows to the astonishment of crowds worldwide. These aerial maneuvers involve both $+G_z$ and $-G_z$ maneuvers, are physically challenging, and leave little margin for error. All U.S. Air Force fighter pilots are given extensive tools and training to overcome the effects of $+G_z$, including centrifuge training, advanced technology anti-G suits (ATAGS), positive pressure breathing for $+G_z$, physical conditioning, and refresher training on the anti-G straining maneuver (AGSM) continuously throughout their careers. Pilots also use peripheral visual tunneling in the aircraft as a warning of impending G-induced loss of consciousness (G-LOC), which may be dangerous since almost loss of consciousness (A-LOC), which usually occurs in short duration, high G-onset rate $+G_z$ exposure, is not usually preceded by peripheral vision loss.[1]

U.S. Air Force fighter pilots are also required to perform a G warmup exercise prior to high $+G_z$ maneuvering, designed to assess G suit inflation and personal G tolerance. This maneuver involves a 90–180° turn, pulling at least $+4$ G_z.[12] An additional benefit of the G warmup exercise is the initiation of the baroreceptor reflex, which increases heart rate, stroke volume, and total peripheral resistance, thereby increasing $+G_z$ tolerance. The increased $+G_z$ tolerance conveyed by the baroreceptor reflex is negated, however, if followed by $-G_z$ exposure.[1] During prolonged $-G_z$ flight, carotid and aortic baroreceptors counteract increased cerebral blood pressure by reducing heart rate and inducing peripheral vasodilation, greatly reducing $+G_z$ tolerance.[2] If a pilot transitions rapidly from prolonged $-G_z$ flight to $+G_z$ flight regimes without giving the cardiovascular system a chance to recover from $-G_z$ effects, the risk of G-LOC greatly increases, especially at high G onset rates (over $2\ G \cdot s^{-1}$).[6] Furthermore, G-LOC can occur after $-G_z$ at much lower $+G_z$ regimes, often with no preceding peripheral vision loss. This is known as the push-pull effect, after the aircraft control inputs necessary to cause it.[3] This F-16 G-LOC was attributed to the push-pull effect.

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CASE REPORT

The mishap pilot (MP) was a physically fit 34-yr-old man assigned to the squadron as "#4." He had over 1400 total flying hours and was a current and qualified Flight Lead and Instructor Pilot with over 500 h in the F-16. He was current on all Aerospace Physiology training. Prior to the mishap sortie, the MP was seen correctly donning his ATAGS, including zipping the comfort zippers, and accomplishing all required connections and checks. After the crash, a postmortem tissue examination detected no carbon monoxide, ethanol, or illegal substances. The mishap aircraft (MA) was an F-16CM built in 1991. All required maintenance actions were properly performed and documented prior to the mishap, although all MA fluid samples were destroyed on impact. The MA Data Acquisition System (DAS, which includes the crash-survivable memory unit) analysis indicated all flight controls, hydraulics, fuel, and engine systems were operating normally and responding to pilot inputs at the time of impact, indicating the MA was mechanically sound during the mishap sortie.[12]

The MP was practicing a "high bomb-burst" maneuver and was executing the final portion (known as the "rejoin") when the mishap occurred. The high bomb-burst rejoin is depicted in **Fig. 1**, and requires #4 (the MP) to execute a $+G_z$ vertical pull to inverted flight known as an Immelmann (an ascending $+G_z$ half loop, which results in a higher altitude, $-G_z$ inverted aircraft attitude, ending with the aircraft heading in the opposite direction). This is then followed by prolonged inverted flight (about 22 s in this mishap) in order to maintain visual contact with #1. The rejoin culminates in a rapid transition from $-G_z$ to $+G_z$ in the form of a split-S maneuver (an inverted descending half loop that results in a lower altitude/opposite direction, wings level $+1\ G_z$ aircraft attitude). Pilot #4 was to complete the rejoin into the "slot" position in the diamond, directly behind #1, no lower than 300 ft (92 m) above ground level (AGL).[12]

The first two portions of the mishap maneuver (the Immelmann and inverted flight) were accomplished uneventfully. The MP began the Split-S rejoin inverted at an altitude of about 8700 ft (2652 m) mean sea level (MSL), about 5700 ft (1737 m) AGL, at an airspeed of 425 knots calibrated airspeed (KCAS) (787 km/ h).[12] In order to optimize his spacing in the rejoin with #1, the MP first maneuvered the MA from $-0.9\ G_z$ to $-2.06\ G_z$ by commanding a forward stick push while inverted (known as a "$-G_z$ pushover") to increase the MA's altitude. The MP then immediately began the $+G_z$ Split-S pull to a maximum of $+8.56\ G_z$. Beginning at 17:29:04 Coordinated Universal Time (UTC) (10:29:04 Local time), the MA DAS recorded only minimal flight control inputs for approximately 5 s, indicating the MP was not in control of the MA. This duration of incapacitation was due to either G-LOC or A-LOC. The MA then unloaded to about $+1.0\ G_z$, simultaneously entering a dive at 68° nose low at a descent rate of 38,500 ft $\cdot$ min^{-1} (11,735 m $\cdot$ min^{-1}). Just prior to impact, the DAS recorded a rapid increase in throttle (from idle to maximum nonafterburner power) and back stick pressure, indicating the MP had regained some awareness, and was attempting to recover the MA. This recovery attempt was interrupted by ground impact, which occurred with the MA in a 60° nose low, 90° left bank attitude, at an airspeed of 419 KCAS (776 km/h). The MP did not attempt ejection. The AIB determined that once the MA descended below 2300 ft (700 m) AGL, a safe recovery above the ground was not possible.[12] The mishap maneuver is depicted in **Fig. 2**.

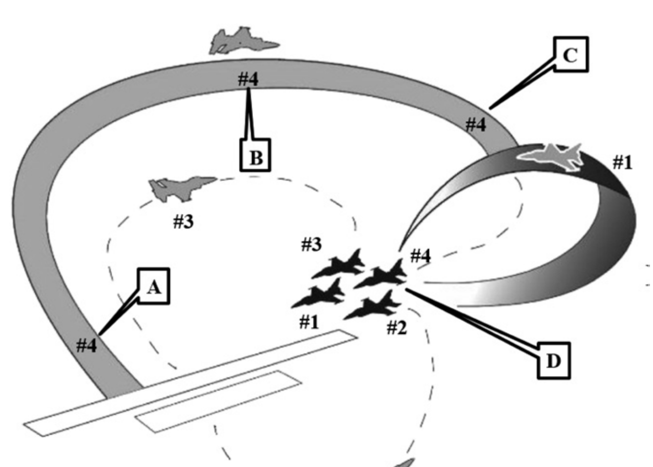

Fig. 1. Maneuvers executed by #4 during high bomb burst rejoin. A) #4 flies an Immelmann: ascending $+G_z$ half loop, ending in inverted flight. B) Prolonged inverted flight required for #4 to maintain visual contact with #1 to accomplish the rejoin. C) Split-S flown by #4: a $+G_z$ descending inverted half loop, rolling out in level flight. The highest risk of G-LOC is from the push-pull effect. D) Maneuver completion: #4 rejoins in the "Slot" position directly behind #1 in the diamond formation.

Fig. 2. Mishap pilot during the high bomb burst rejoin maneuver on the day of the mishap. MA parameters across the bottom of the figure correspond to the maximum $+G_z$ during the Split-S, at 17:29:03 UTC (1 s prior to G-LOC). Top row, left to right: airspeed (372 KCAS); attitude indicator: approx. 90° nose low and 5–10° left bank; altimeter: 7266 ft MSL (4266 ft AGL); engine RPM: 82%; turbine inlet temperature (FTIT): 690°C. Bottom row, left to right: angle of attack (AOA): 16.5; vertical velocity indicator (VVI): descending at 39,700 FPM (ft $\cdot$ min^{-1}); heading indicator: 234° (west-southwest); acceleration G units: $+8.6\ G_z$; engine nozzle position (NOZ POS): 21% open; fuel flow: $<$ 1000 lb $\cdot$ h^{-1} (normal for idle power). Far right, top: throttle setting: idle power; stick position: aft stick; rudder position: neutral. Far right column: caution/warning panel: no cautions or warnings illuminated.

When the MP initiated the Split-S rejoin, it was immediately after sustaining $-G_z$ flight for 22 s. Furthermore, the MP pushed the nose of the MA up into an even further $-G_z$ flight regime immediately prior to initiating the Split-S. At this point, the MA went through a magnitude of 10.5 G_z, starting at -2.06 G_z, pulling to +8.56 G_z in 5 s. This is followed by the DAS recording only minimal flight control inputs, indicating MP incapacitation. This is an operational example of the push-pull effect reducing a pilot's ability to tolerate +G_z when immediately preceded by prolonged $-G_z$. These G regimes are shown graphically in **Fig. 3**. The first second of the Split-S rejoin maneuver resulted in a 5.67 $G \cdot s^{-1}$ onset rate, as noted in the initial steepness of the Split-S G curve. At the maximum of +8.56 G_z, the MP experienced either G-LOC or A-LOC, as shown by the rapid decrease in G_z between the Split-S max G_z, and the recovery attempt on Fig. 3. Subsequently, the MP regained enough cognitive ability to attempt recovery, although too late to avoid ground impact. The AIB concluded the cause of the mishap was the MP's G-LOC due to diminished tolerance to +G_z induced by the push-pull effect, and a decrease in the MP's AGSM effectiveness under those conditions.[12]

The high bomb burst maneuver has been performed by the mishap squadron for the past 35 yr without any G-LOC fatalities. To determine what was different about the mishap maneuver, The AIB compared the mishap rejoin to heads-up display (HUD) recordings of previous rejoins accomplished by the MP. The pertinent results of these HUD reviews are summarized in **Table I**. These show that both the $-G_z$ just before the mishap Split-S, combined with the G_z differential (10.5 G_z) of the mishap Split-S were higher than any previous recorded Split-S maneuvers, predisposing the MP to G-LOC due to the push-pull effect.[2] Furthermore, the mishap Split-S did not have any recorded $-G_z$ unloading prior to the +G_z pull, as previous Split-S maneuvers did. Concurrently, the highest magnitude $-G_z$ (-2.06 G_z) was recorded immediately prior to the maximum G-onset rate, indicating the MP pushed the MA into a greater $-G_z$ regime just prior to initiating the Split-S.[12] The MP most likely did not notice pushing the MA to -2 G_z, since his attention was divided between looking outside at #1 to optimize his rejoin geometry while simultaneously making stick and throttle changes. While the current G level is depicted in the F-16 HUD, most fighter pilots do not consult this data to perform tactical maneuvers, since visual cues tend to trump G levels while maneuvering. Because of this, combined with his division of attention, he was most likely not concentrating on the G meter on the HUD or inside the cockpit.

DISCUSSION

This is not the first example of a fatal crash caused by the push-pull effect. In 1995, a Canadian Air Force CF-18 Hornet was lost under similar circumstances.[5] Other studies have shown that the push-pull effect has caused multiple G-LOC mishaps in the past, both in the U.S. Air Force and the Royal Air Force.[7,8] Though the adverse effects of the push-pull maneuver have been known for 25 yr, this crash points to the continuing need to educate both military and GA aircrew about this hazard,

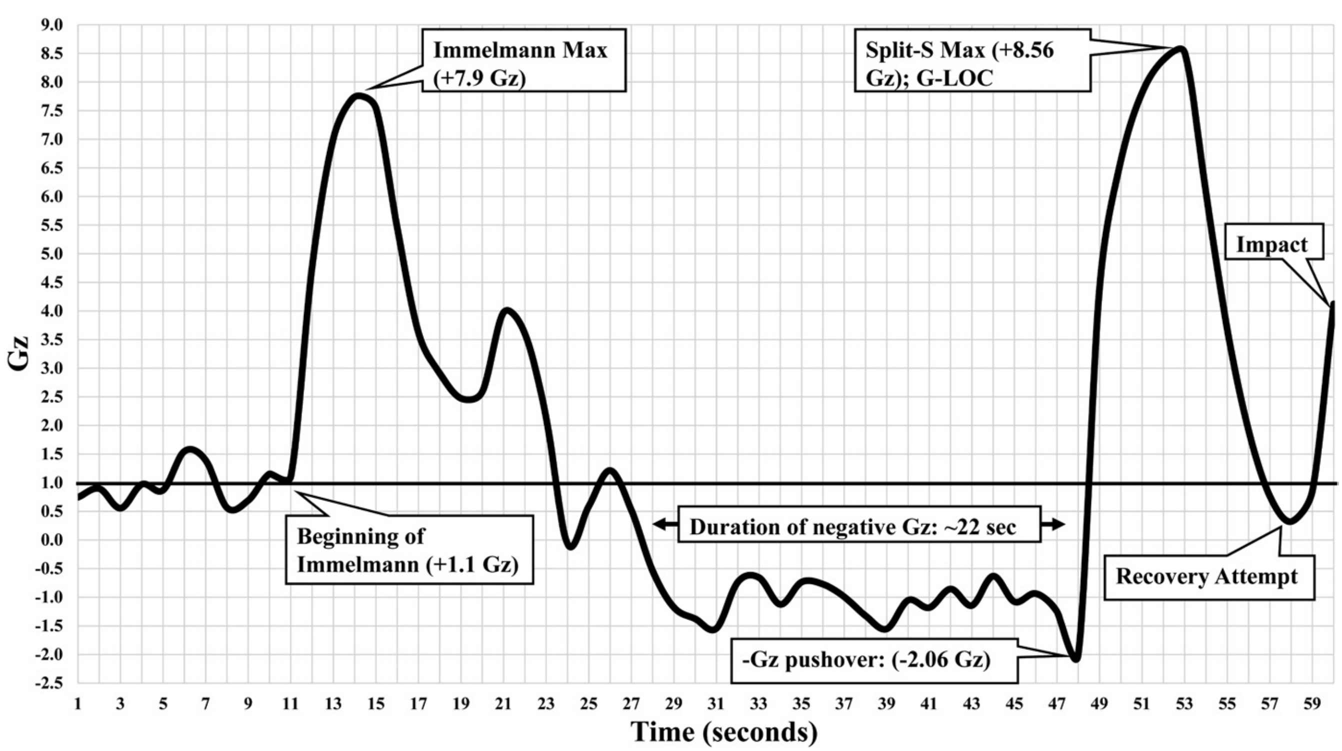

Fig. 3. G_z sustained during the mishap maneuver.

Table I. Mishap Pilot's Recorded G_z from Heads-Up Display Tapes.

DATE (2018)	$-G_Z$ FLIGHT DURATION	MAX $-G_Z$	G_Z RECORDED JUST BEFORE SPLIT-S	G ONSET RATE DURING FIRST SECOND OF SPLIT-S	DURATION OF SPLIT-S FROM BEGINNING OF PULL TO MAX $+G_Z$	MAX $+G_Z$ DURING SPLIT-S	G_Z DIFFERENTIAL FROM BEGINNING OF SPLIT-S TO MAX $+G_Z$
29 Jan.	22 s	−1.8	−0.9	4.5 G • s^{-1}	3 s	+7.7	8.6 G_z
5 Feb.	**20 s**	**−2.2**	**−1.7**	**5.5 G • s^{-1}**	**3 s**	**+7.3**	**9.0 G_z**
15 Feb.	23 s	−1.9	−1.3	5.2 G • s^{-1}	3 s	+6.9	8.2 G_z
20 Feb.	20 s	−1.7	−0.9	4.7 G • s^{-1}	4 s	+7.3	8.2 G_z
21 Feb.	19 s	−1.9	−0.8	4.9 G • s^{-1}	4 s	+7.6	8.4 G_z
28 Feb. (1)	**20 s**	**−2.2**	**−1.0**	**5.2 G • s^{-1}**	**4 s**	**+8.0**	**9.0 G_z**
28 Feb. (2)	22 s	−2.0	−0.3	5.0 G • s^{-1}	3 s	+7.8	8.1 G_z
5 Mar.	**25 s**	**−1.6**	**−0.4**	**5.6 G • s^{-1}**	**3 s**	**+7.9**	**8.3 G_z**
6 Mar. (1)	20 s	−1.4	−0.5	5.2 G • s^{-1}	4 s	+7.6	8.1 G_z
6 Mar. (2)	22 s	−1.9	−0.1	5.6 G • s^{-1}	3 s	+8.4	8.5 G_z
8 Mar.	**21 s**	**−2.2**	**−0.7**	**4.2 G • s-^{1}**	**6 s**	**+8.0**	**8.7 G_z**
16 Mar. (1)	**20 s**	**−2.2**	**−1.0**	**5.0 G • s^{-1}**	**4 s**	**+8.0**	**9.0 G_z**
16 Mar. (2)	**20 s**	**−1.5**	**0.0**	**5.8 G • s^{-1}**	**3 s**	**+8.5**	**8.5 G_z**
17 Mar.	19 s	−2.0	−0.6	4.6 G • s^{-1}	3 s	+7.4	8.0 G_z
19 Mar.	17 s	−2.5	−0.5	3.8 G • s^{-1}	3 s	+6.3	6.8 G_z
4 April (Mishap Rejoin)	**22 s**	**−2.05**	**−2.05**	**5.67 G • s^{-1}**	**5 s**	**+8.56**	**10.5 G_z**

The last row depicts the mishap rejoin recorded G_z for comparison. Rejoins similar to the mishap rejoin are in bold.

warning pilots to avoid $-G_z$ regimes if possible. There are several points to take away from this mishap that may be passed on to prevent future mishaps. Firstly, although an automatic ground collision avoidance system would likely have prevented this fatality, the squadron was not using this system at the time of the mishap due to the risk of an uncommanded activation causing a midair collision in close formation. Secondly, though the AIB attributed this mishap to G-LOC, it was probably A-LOC due to the short timeframe of the MP's incapacitation. However, given that A-LOC results in the same operational incapacitation as G-LOC, The U.S. Air Force usually does not differentiate between the two during physiological training.[1] Rather than being considered a discrete phenomenon, A-LOC should be included in a broader G-LOC definition, such as the "G-LOC Syndrome" described by Morrissette and McGowan,[9] and discussed in research by Shender et al.[10] and Slungaard et al.[11] This enhanced definition of G-LOC encompasses the entire continuum of A-LOC and G-LOC and allows for easier aircrew education.

Thirdly, U.S. Air Force fighter pilots usually initiate the muscle tensing and preparatory breath of the AGSM prior to pulling the aircraft into high $+G_z$ regimes. During the mishap maneuver, however, the MP was inverted when he would usually initiate the AGSM. In discussions with the mishap squadron, specifically #4 (who replaced the MP after his death), their technique was to relax lower body muscles during inverted flight to lessen the effects of $-G_z$. Had the MP done a proper AGSM in this instance, it would have forced even more blood cephalad, exacerbating the detrimental symptoms of $-G_z$. Therefore, it can be inferred that the MP did not initiate an AGSM until well into the $+G_z$ regime of the Split-S rejoin, effectively placing him behind the time when he should have begun his AGSM. Pilots refer to this as being "behind the Gs", and this may be another reason the push-pull maneuver is so dangerous: a properly executed AGSM during $-G_z$ flight would actually make any $-G_z$ symptoms more severe, and may increase the likelihood of G-LOC or A-LOC. Furthermore, although the MP was physically fit, this alone does not reduce the risk of G-LOC due to the push-pull effect.[12] Finally, the risks of the push-pull effect are not limited to high performance military aircraft. Banks et al. proved that the deleterious effects of push-pull maneuvering can be elicited with Gs as mild as -2 G_z and +2.25 G_z, well within the G tolerance of most GA aircraft, including helicopters.[2] For example, the design load factor tolerance of a Cessna-172 (a common GA training platform) is -2.28 to +5.7 G_z (normal category, flaps up).[4] Both civilian and military flight instructors (including rotary wing) should educate themselves and their students about the threat of the push-pull effect. If prolonged inverted flight or $-G_z$ maneuvering is operationally necessary, instructors should teach student pilots to unload the aircraft to the $+G_z$ regime (if practical) prior to pulling maximum $+G_z$.

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