Analysis of multi-axis acceleration profile in a Supermanoeuvrable aircraft

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ABSTRACT

Supermanoeuvrable aircraft, in addition to sustaining high +Gz acceleration during conventional air combat, is capable of manoeuvring in all the three axes because of its unique aerodynamic geometry. The acceleration profiles of such an aircraft were studied to quantify the extent of in-flight acceleration stress during multi-axis fighter manoeuvres. Randomised selection of multi-axis manoeuvre sorties was done. The relevant data was collected from graphs and / or digital print outs of the flight data recorder and data processing system and was analysed to study the in-flight acceleration environment. The mean duration of time for which the aircrew were exposed to multi-axis acceleration was 840.96 seconds and it was observed that the aircraft was manoeuvring in combined transverse (Gx) and vertical (Gz) axes for the major portion of the time. The average peak + Gz acceleration achieved was 6.72 G with a mean onset and offset rate of 3.09 G/s and 2. 66 G/s respectively. Acceleration in other axes revealed that the mean peak G was 1.07 G in + Gx axis, 0.25 G in – Gx axis, 0.42 G in +Gy axis and 0.56 G in -Gy axis. The mean peak level of combined acceleration was observed to be 1.07/6.06 G for +Gx/+Gz, -0.25/1.15 G for -Gx/+Gz, 0.42/2.60 G for +Gy/+Gz and -0.56/1.95 G for -Gy/+Gz. Even though the aircraft was going into -Gz at times during these manoeuvres, the magnitude of combined acceleration in this axis was negligible. This study revealed that the aircraft is capable of manoeuvring in all the three axes. The multi-axis acceleration stress, when Gz, Gx and Gy are experienced together is unique to the aircraft.

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The in-flight environment of any combat aircraft is a unique multi-stress environment; the acceleration stress is unavoidable in this flying milieu. Introduction of advanced technology such as incorporation of electronic flight control system and better thrust to weight ratio has significantly increased the combat capabilities of a modern fighter aircraft. A higher thrust to weight ratio implies that under high 'G' conditions, the engine has sufficient power to prevent the speed from decaying, thus resulting in high-sustained acceleration (HSG) stress [1]. In addition, electronic flight controls allow very high onset rates so that the aircrew may lapse into unconsciousness without passing through visual warning symptoms. Thus, in the modern high performance aircraft, the acceleration stress continues to affect the physical, physiological and psychological aspects of the aircrew and hence the performance [2].

Air combat depends upon the performance capabilities and manoeuvrability of the aircraft. Combat manoeuvring is essential in any tactical mission, in terms of the ability to change the direction of flight path to gain energy and position advantage over the opponent [1]. However air

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combat is the most stressful event during a fighter mission. During air combat manoeuvring (ACM), significant acceleration forces are repeatedly applied to the fighter pilot, and the potential adverse physiological consequences, viz. G-Induced Loss of Consciousness (GLOC) and Almost Loss of Consciousness (ALOC) are well known.

Supermanoeuvrable aircraft with its unique aerodynamic geometry and thrust vectoring control system is capable of performing difficult manoeuvres [3]. Supermanoeuvrability is defined as the capability to execute manoeuvre with controlled sideslip at angles of attack well beyond those for maximum lift. These capabilities include multi-axis accelerations, and unprecedented angular velocities and accelerations around the three principal axes of the aircraft. Multi-axis sustained accelerations, such as those experienced when flying thrust vectored aircraft, can have an effect on G-tolerance of the pilot depending upon the direction and duration of the exposure [4]. So also the consequences of 'push pull effect' on +Gz tolerance have been well documented [5].

The present study intends to analyse the acceleration profiles of a supermanoeuvrable aircraft during multi-axis manoeuvring. This study has been done to understand the in-flight acceleration environment, to which the aircrew of a supermanoeuvrable aircraft are exposed. This knowledge will be useful for aircrew training, aeromedical evaluation and research.

Material and Methods

24 pilots from two different squadrons, operating supermanoeuvrable aircraft, participated in the study and seven aircraft were utilised to collect the relevant data. The mean age of the pilots was 32.62 ± 3.68 years. Each pilot had considerable flying experience - an average of 1533.3 hours for day and 175.4 hours for night flying. Randomised selection of multi-axis sorties(n=29) was done to study the in-flight acceleration stress. Details of the sorties are depicted in Table 1.

Data collection

The data was collected from the flight data recorder (FDR) of the aircraft. This stored information was transferred to the ground based flight data processing system to obtain computer based solutions for analysis of the recorded data. The relevant parameters pertaining to G stress were derived. The data was analysed to figure out the in-flight acceleration environment during multi-axis manoeuvring.

Results

The present study analysed twenty nine (29) multi-axis manoeuvre sorties to assess the acceleration stress imposed on the pilots of a supermanoeuvrable aircraft. Analysis of the altitude profile revealed that the average range of altitude varied between 661 m to 3535 m during multi-axis manoeuvring. The range of indicated air speed (IAS) varied from 54 to 821 Km/h and the average pitch angle or angle of attack (AOA) ranged from – 1.70° to 38.03° (Table 1).

Table 1 : Altitude, IAS and AOA during multi-axis manoeuvres

Parameters	Mean	SD
Altitude (Metre)		
Minimum	661.48	328.96
Maximum	3535.13	993.03
IAS (Km/Hr)		
Minimum	54.65	45.26
Maximum	821.44	83.14
AOA (°)		
Minimum	-1.70	3.52
Maximum	38.03	3.04

It was observed that the mean duration for which the aircrew were exposed to multi-axis acceleration was 840.96 s with a range of 335 to 1136 s. The mean duration of stay in transverse axis at different G levels was 11.34 s more than 1 G, 452.31 s between 0.5 to 0.99 G, 234.31 s below 0.5 G for + Gx and 47.68 s below 0.5 G for - Gx. Similarly the mean duration of stay below 0.5 G in lateral axis was 19.34 s for + Gy and 21.89 s for – Gy (Table 2). The maximum duration of stay at peak G levels (> 1 G) was noted to be 56 s for + Gx, 1 s for + Gy and 1 s for – Gy.

Table 3 shows the Gz profile during multi-axis manoeuvring. The average peak + Gz acceleration achieved was 6.72 G with a range of 5.77 to 7.51 G. The maximum onset rate varied from 0.81 to 5.82 G/s with a mean of 3.09 G/s. Similarly the maximum offset rate ranged from 1.3 to 4.62 G/s with a mean of 2.66 G/s. In addition + Gz stress was frequently repetitive (Table 4).

Analysis of peak G in other axes (Table 5) revealed that the mean peak G in + Gx axis was 1.07 G with a range of 1 to 1.23 G and in – Gx axis was 0.25 G with a range of 0.1 to 0.58 G. The peak acceleration varied from 0.2 to 1.06 G with a mean of 0.42 G in + Gy axis and from 0.11

Table 2 : Duration of stay in other axes

G levels during Multi-axis sortie (G)	Duration (Seconds) Gx		Gy	
	Mean	SD	Mean	SD
1.49-1	11.34	13.35	0.03	0.18
0.99-0.5	452.31	128.05	0.103	0.409
0.49-0	234.31	92.52	19.34	9.84
0-(-) 0.49	47.68	37.51	21.89	8.73
(-) 0.5 - (-) 0.99	0.10	0.55	0.72	1.43
<- 1	-	-	0.06	0.25

Table 3 : 'Gz' profile during multi-axis manoeuvres

Parameters	Maximum	Minimum	Mean	SD
Duration of Multi - axis acceleration (Sec)	1136	335	840.96	232.45
Peak Gz (G)	7.51	5.77	6.72	0.37
Minimum Gz (G)	0.73	-0.12	0.30	0.22
Max. Rate of Onset (G/Sec)	5.82	0.81	3.09	1.12
Max. Rate of Offset (G/Sec)	4.62	1.3	2.66	0.87

Table 4 : Frequency of stay at 2 Gz and above during a multi-axis sortie

'Gz' Levels (G)	Frequency Maximum	Minimum	Mean	SD
2 – 2.99	59	22	42.31	10.68
3 – 3.99	41	14	29.27	8.39
4 – 4.99	28	9	19.06	6.02
5 – 5.99	14	2	8.51	3.13
6 – 6.99	5	0	2.03	1.26
7 – 7.99	2	0	0.20	0.49

to 1.08 G with a mean of 0.56 G in – Gy axis. The mean peak level of combined acceleration was observed to be 6.72/0.96 G with a range of 5.77/0.52 to 7.51/1.21 G for +Gz/+Gx. Similarly the maximum peak combined acceleration observed was 4.52/1.06 G for +Gz/+Gy and 3.67/ -1.08 G for +Gz/-Gy (Table 6).

Table 5 : Peak 'G' in different axes

Peak G (G)	+Gz	+Gx	-Gx	+Gy	-Gy
Maximum G	7.51	1.23	0.58	1.06	1.08
Minimum G	5.77	1	0.1	0.2	0.11
Mean G	6.72	1.07	0.25	0.423	0.56
SD	0.37	0.129	0.12	0.20	0.23

Table 6 : Combined acceleration stress during multi-axis manoeuvres

Peak level of combined acceleration	Maximum G	Minimum G	Mean G	SD
Peak + Gz/Gx	7.51/1.21	5.77/0.52	6.72/0.96	0.37/0.16
Peak + Gz/Gy	7.51/0.03	5.77/ -0.11	6.72/ -0.04	0.37/0.03
Peak + Gx/Gz	1.23/7.13	1.02/4.61	1.07/6.06	0.05/0.69
Peak – Gx/Gz	-0.58/2.1	-0.1/0.27	-0.25/1.15	0.12/0.35
Peak + Gy/Gz	1.06/4.52	0.2/0.88	0.42/2.60	0.20/0.97
Peak – Gy/Gz	-1.08/3.67	-0.02/0.67	-0.56/1.95	0.23/0.68

Discussion

The study was intended to document the in-flight acceleration stress to which the aircrew of a high endurance, air dominant, supermanoeuvrable fighter aircraft are exposed during multi-axis manoeuvring. The results of the study clearly demonstrate the nature and characteristics of acceleration environment in these manoeuvres.

Altitude, IAS and AOA profile

Analysis of the altitude profile per flight revealed that multi-axis manoeuvres were executed between 661 m to 3535 m. Multi-axis manoeuvring which typically involved low level aerobatics and low speed handling sorties are usually exhibited at low to medium altitudes. Manoeuvrability of an aircraft is better at low altitudes because altitude has a significant influence on the instantaneous turn performance [1]. During the manoeuvre mode, while performing certain difficult manoeuvres the speed dropped on an average to as low as 54 Km/h. The intersection of the positive aerodynamic boundary and structural limit defines a speed that is crucial in fighter performance. This is known as corner speed or manoeuvring speed [1, 6]. Supermanoeuvrable aircraft has the minimum manoeuvring speed meaning that the aircraft had the capability of optimum turn performance at slow speeds. The average pitch angle ranged from -1.7° to 38.03°. The high magnitude and rate of change of AOA adds on to the manoeuvring capability of the aircraft. The aerodynamic configuration of supermanoeuvrable aircraft increases the aircraft lifting effectiveness and allows high AOA flights [3, 7].

Acceleration profile

Out of a total of 29 sorties analysed, it was observed that the mean duration of time for which the aircrew were exposed to multi-axis acceleration was 840.96 s with a range of 335 to 1136 s. Analysis of duration of stay at specific G levels in different axes revealed that the aircraft was manoeuvring in combined transverse (Gx) and vertical axes (Gz) for the major portion of the time. The time spent above 0.5 G in lateral axis and –Gx was negligible. The peak acceleration above 1 G was observed in transverse axis in all the sorties and in lateral axis in only very few occasions. However, it was seen from the study that the aircraft has the capability of performing multi-axis manoeuvres in all the three axes.

The peak + Gz acceleration ranged from 5.77 to 7.51 G with a mean value of 6.72 G. The onset and offset rates were observed to be much higher. In addition the + Gz stress was frequently repetitive. Analysis of combined acceleration profile showed that the combination of +Gx to +Gz was high in most of the sorties while the combination of high magnitude of +Gy or -Gy to +Gz was seen only on few occasions. Even though the aircraft was going into –Gz and –Gx at times during these manoeuvres, the magnitude of combined acceleration in these axes were negligible.

Multi-axis manoeuvring in supermanoeuvrable aircraft is made feasible by a series of factors such as thrust - weight ratio, vectored thrust, an electronically monitored control system and unique aerodynamic features especially a negative stability margin [3]. The provision of canards offers additional control movement and thus allows the AOA to reach very high values. With the AOA increased to very high values above those for maximum lift, the aircraft was able to manoeuvre in less air space in significantly shorter period of time and by directing thrust vectoring control system in longitudinal and lateral planes, it was capable of significant excursions in Z, X and Y axes [8, 9].

Anticipated acceleration stress

Altitude independent accelerations along all three axes and unlimited flight independent rotational excursions about pitch and yaw axes in supermanoeuvrable aircraft, as evidenced from this study can have an effect on Gz tolerance depending upon the net gravitational forces [4]. The possible effect of multi-axis acceleration on G tolerance needs to be discussed.

Centrifuge studies on the effects of combined acceleration revealed a small but definite fall in percentage saturation of arterial oxygen (Sa O_2), more with lateral acceleration, worst being + Gy [10]. Further it was observed that addition of moderate +Gx significantly reduced +Gz tolerance [4]. If the physiological effects of +Gz acceleration is assumed to be a consequences of tissue hypoxia, then a decreased SaO_2 would have a significant effect on +Gz tolerance.

Multi-axis acceleration induces unusual vestibular stimulation, which can affect the G tolerance through vestibular generated cardiovascular responses. The cardiovascular effects of coriolis cross coupling were highlighted by Sinha et al [11]. He found that the vestibular cross coupling caused an impairment of sympathetic activity resulting in vasodilatation, thus impairing orthostatic tolerance. The cardiovascular responses to roll versus pitch rotation was studied by Cheung et al [12] and his findings suggested that there was relatively poor cardiovascular compensation for roll rotation. Urschel et al [13] demonstrated that high angular acceleration of the head about the yaw axis reduced the baseline baroreflex mechanisms by 30%. All these findings provide support for the influence of vestibular system on sympathetic outflow in human and is a concern for G tolerance in the pilots flying supermanoeuvrable aircraft.

Conclusion

The mean duration of time for which the aircrew were exposed to multi-axis acceleration was 840.96 seconds and it was observed that the aircraft was manoeuvring in combined transverse (Gx) and vertical (Gz) axes for the major portion of the time. The average peak + Gz acceleration achieved was 6.72 G with a mean onset and offset rate of 3.09 G/s and 2. 66 G/s respectively during multi-axis manoeuvring. Acceleration in other axes revealed that the mean peak G was 1.07 G in + Gx axis, 0.25 G in - Gx axis, 0.42 G in +Gy axis and 0.56 G in -Gy axis. The mean peak level of combined acceleration was observed to be 1.07/ 6.06 G for +Gx/+Gz, -0.25/1.15 G for -Gx/+Gz, 0.42/2.60 G for +Gy/+Gz and -0.56/1.95 G for Gy/ +Gz. Even though the aircraft was going into -Gz at times during these manoeuvres, the magnitude of combined acceleration in this axis was negligible.

This study revealed that the aircraft is capable of manoeuvring in all the three axes. The multi-axis acceleration stress, when Gz, Gx and Gy are experienced together, is unique to this aircraft.

References

1. Shaw RL. Fighter combat: The art and science of air-to-air combat. 2nd edition. Northamptonshire: Patrick Stephens Ltd; 1988.

2. Leverett SD Jr, Whinnery JE. Biodynamics: Sustained acceleration. In: DeHart RL, Davis JR, editors. Fundamentals of Aerospace Medicine. 3rd edition. Philadelphia: Lippincott Williams and Wilkins, 2002 : 122 - 153.

3. Vayu sena. http://www. bharat rakshak.com/iaf/ vayusena.html. Accessed on 20 October 2006

4. Albery WB. Acceleration in other axes affects + Gz tolerance. Dynamic centrifuge simulation of agile flight. Aviat Space Environ Med 2004; 75: 1-6.

5. Tyagi PK. Push - pull effect. Ind J Aerospace Med 2001;45: 8-13.

6. Walker SR. Basic fighter Manoeuvre. In : Air power. Aircraft, weapon systems and technology series. Volume - 5: Air superiority operations. 1st edition. New Delhi: Ritana Books; 1995.

7. Singh J. Air power in modern warfare. 1st edition. New Delhi: Lancer International, 1985.

8. Albery WB. Human consequences of Superman-oeuvrable flight. SAFE Journal 2000; 30: 156-164.

9. Lyons T. Albery W, Banks R. Human consequences of agile flight. Final technical report TR-105. NATO RTO working group; 27 May 2001.

10. Popplow J, Veghte J, Hudson K. Cardiopulmonary responses to combined lateral and vertical acceleration. Aviat Space Environ Med 1983; 54: 632-6.

11. Sinha R. Effects of coriolis reaction on respiration and blood-flow changes in man. Aerospace Med 1968; 39: 837-44.

12. Cheung B, Hofer K, Goodman L. The effects of roll versus pitch rotation in humans under Orthostatic stress. Aviat Space Environ Med 1999; 70: 966-74.

13. Urschel CW, Hood WB. Cardiovascular effects of rotation in the z-axis. Aerospace Medicine 1966; 37: 254-6.