FLIGHT IN SEVERE TURBULENCE

A CLOSE ENCOUNTER OF THE ROUGH KIND

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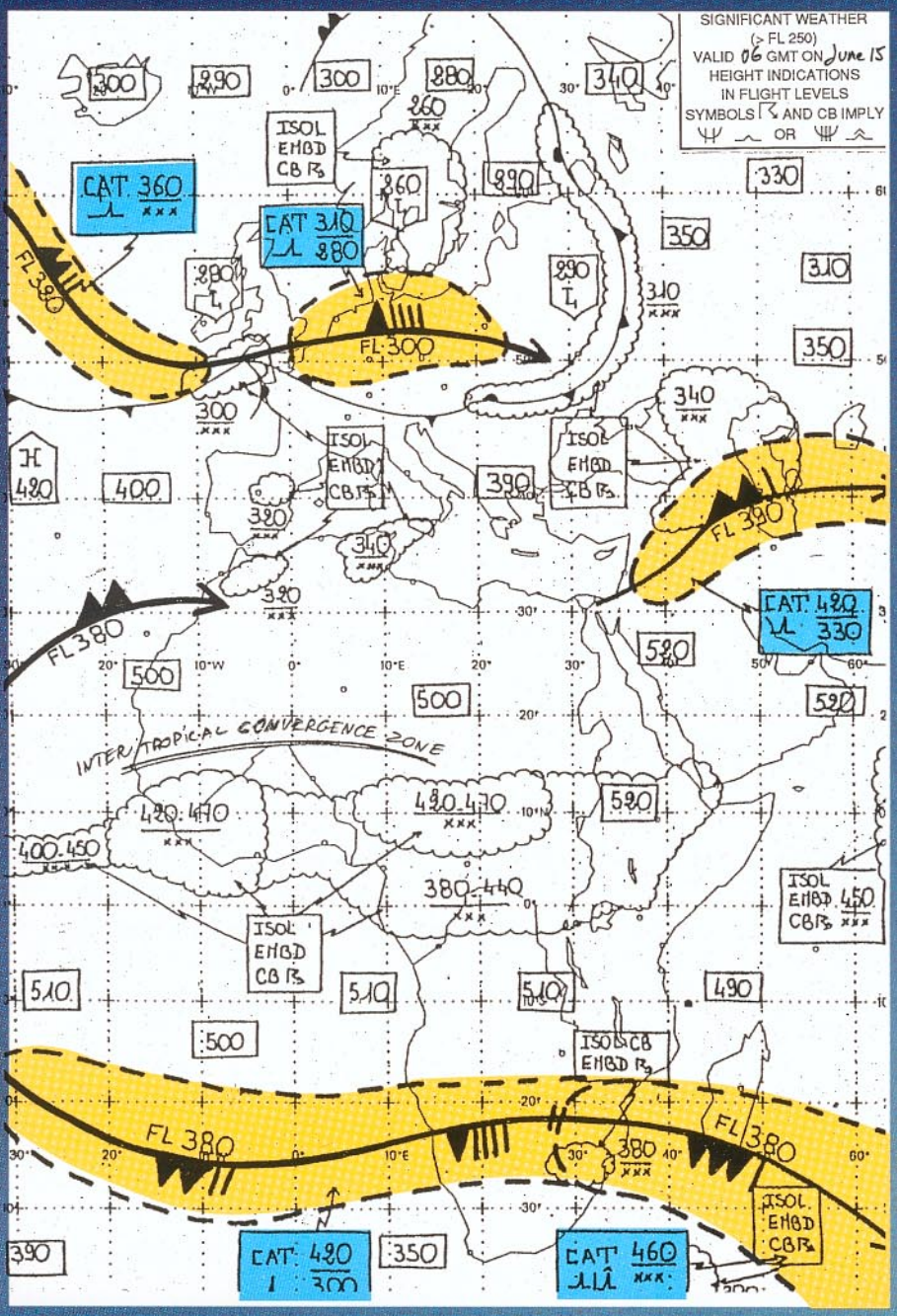

A turbulence encounter is a play featuring three characters:
the atmosphere,
the aircraft and the pilot (whether a human pilot or an auto-pilot).
The purpose of this article is to review the respective role and contribution of these three actors, through the main aspects associated with flying in severe turbulence at altitude.

Most of the considerations addressed in this article are general in nature and are equally applicable to the A300/A310/A300-600 and to the A320/A330/A340 aircraft families.

Whenever applicable, specific considerations are given for non-fly-by-wire and fly-by-wire models respectively.

TURBULENCE ENCOUNTERS AND AVIATION SAFETY

Severe turbulence encounters at altitude have been experienced worldwide by all models of jet transports, sometimes resulting in injuries to passengers and cabin attendants.

The statistical data related to turbulence encounters reveal that narrowbody and widebody aircraft of all types and models are equally affected. A survey performed by the US FAA and the Flight Safety Foundation revealed that turbulence causes twice as many serious injuries to passengers and cabin attendants as does emergency evacuations.

The particular nature of flight in severe turbulence and its possible consequences, in terms of passengers or crew injuries and/or aircraft damage, should not be underestimated and should be highlighted whenever and wherever applicable.

DEFINING SEVERE TURBULENCE

Considerations and procedures related to flight in severe turbulence are applicable only when such ***severe*** or ***very severe*** turbulence conditions are encountered. ICAO defines the turbulence severity as a function of the vertical acceleration at the aircraft centre of gravity and as a function of the turbulence effect on the aircraft flight, as defined in Table 1.

Severe turbulence is sometimes defined as a turbulence level which impairs reading of the cockpit instruments and / or gauges. A combination of criteria based on years of flying experience undoubtedly constitutes the best blend for defining severe or very severe turbulence conditions.

An exhaustive overview of all the possible causes of turbulence would exceed the scope and size of this FAST magazine. The interested reader may refer to the numerous books available in aviation book shops. One of these publications provides a comprehensive and truly pilot-oriented review of this subject, *"TURBULENCE - A New Perspective For Pilots"* by Peter F. Lester (Jeppesen Sanderson Training Systems).

Table 2 provides a brief synthesis of the various types of turbulence, together with remarks which may assist the flight crews in assessing the potential for severe turbulence based on the analysis of the following data :

- significant weather charts,
- upper winds forecast,
- AIRMET and SIGMET weather report or forecast messages,
- pilots' reports (PIREPS).

Table 1

Defining the level of turbulence

Turbulence severity	*Vertical acceleration (γ)*	*Effect on flight*
Very low	$\gamma \leq \pm 0.05g$	Light oscillations in pitch and roll.
Low	$\pm 0.05g \leq \gamma \leq \pm 0.2g$	Marked frequent oscillations : ride comfort affected.
Moderate	$\pm 0.2g \leq \gamma \leq \pm 0.5g$	Strong intermittent jolts.
Severe	$\pm 0.5g \leq \gamma \leq \pm 1.5g$	Aircraft handling affected.
Very severe	$\gamma > \pm 1.5g$	Unacceptable for passengers' comfort.

Table 2

Forecasting turbulence

Type of turbulence	*Remarks - Forecasting tips*
Convective storm cells	Clear Air Turbulence (CAT) may be expected close to convective storm cells .
Frontal surfaces	Severe turbulence may be expected due to friction of air masses and due to horizontal windshear caused by wind component change across the frontal surface.
Orographic waves Dynamic gravity waves	Turbulence may exist even in the absence of lenticular clouds.
Clear Air Turbulence	CAT may be anticipated whenever one or more of the following conditions are met : • vertical wind gradient (rate of change or Shear Rate) > 5kt / 1000ft (Table 3), • horizontal wind gradient > 40kt / 100nm, • horizontal OAT gradient > 4°C / 100nm, • route is close to the polar side of a jetstream (Figure 1) • route is close to an altitude trough of low pressure. Exiting CAT : • if TAT/SAT increase → climb, • if TAT/SAT decrease → descend.
Jetstreams	Severe turbulence may be expected, if jetstream exceeds 100kt, on its polar side (Figure 1).

Forecasting turbulence

The likelihood of encountering severe turbulence during a given flight can be assessed using the data contained in the standard weather briefing, using the criteria and tips provided in Table 2 and Figure 1.

For Clear Air Turbulence (CAT) due to vertical and/or horizontal wind gradient, the US National Oceanic and Atmospheric Administration (NOAA) has analyzed wind patterns associated with jetstreams around the globe and has defined a Turbulence Index which allows maps of likely areas of CAT to be established.

Some Computerized Flight Plans (CFP) provide a simple index at each waypoint, referred to as the Shear Rate (SR), expressed in kt/1000ft, as illustrated in Table 3. This index represents the vertical wind gradient and constitutes a dependable turbulence indicator.

Moderate turbulence can be expected whenever the Shear Rate is equal to or greater than 3. Severe turbulence can be anticipated whenever the Shear Rate is equal to or greater than 5.

However, it is a fact of life that severe turbulence may be experienced unexpectedly and suddenly during the course of an otherwise smooth ride, despite the sophisticated forecasting techniques available.

In readiness, turbulence anticipated or not, operational recommendations and procedures are published for :

- flight in severe turbulence: turbulence penetration preventing exceedance of maximum operating speeds (VMO/MMO)
- recovery from a turbulence upset: recovery from VMO / MMO exceedance.

Table 3

Computerized Flight Plan (CFP) - Shear Rate (SR)

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POSN    DIST    TC     FL    WIND    TAS   ZT    B/O   .... ....
MSA     DTGO    MH     SR    COMP    GS    ACTM  ACBO
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
N24 14.9 E120 37.3 WATER
WATER    025    200    31    28082   378   0004  0018  .... ....
106     1753    211    06     M040   338   0012  0056  .... ....
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How does turbulence upset the aircraft?

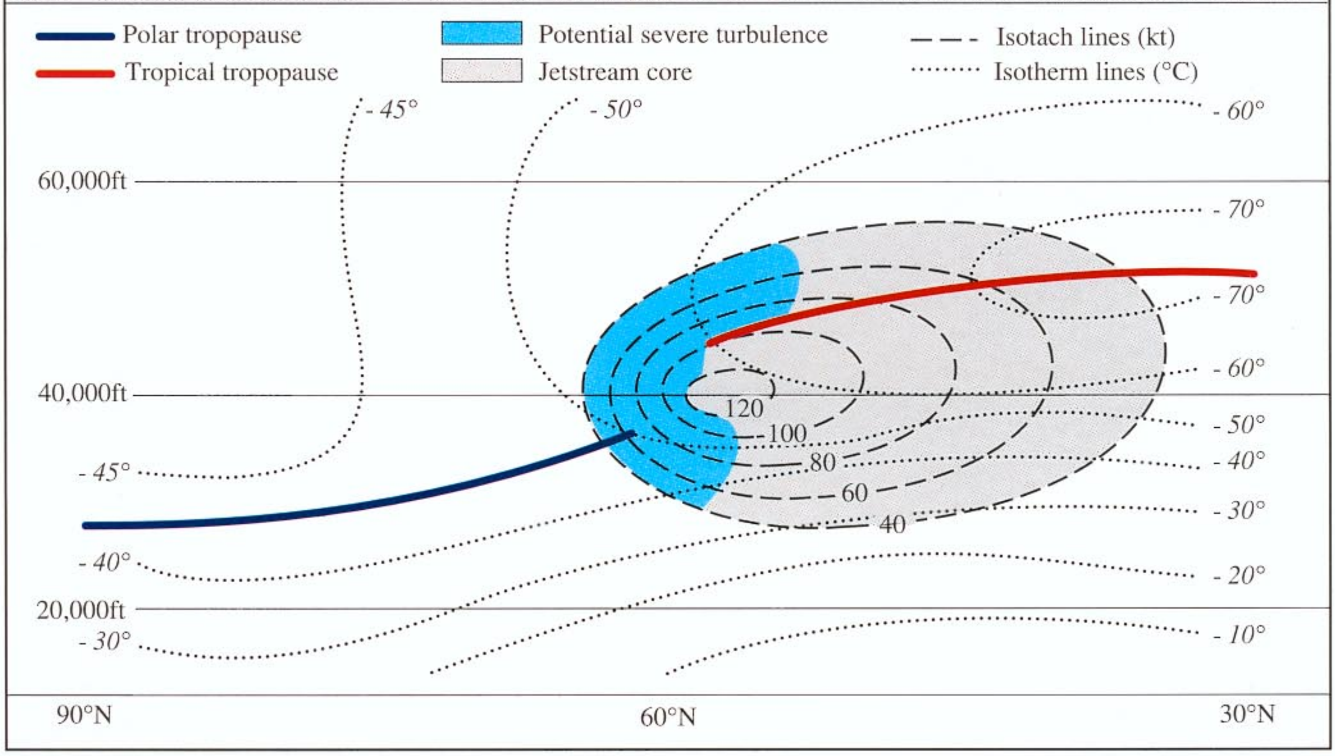
Whether the turbulence is caused by a vertical or a horizontal gust, the gust results in a change in the g-load factor and, usually, in a pitch and airspeed upset. The aircraft design speeds and structure are defined to account for the above overload and overspeed conditions resulting from a defined gust being experienced at the aircraft cruise design speed.

The analysis of events' data, related to Airbus and non-Airbus aircraft, reveals the following possible variations as a result of a turbulence upset :

- ***Vertical gust:***
  - 2,000 to + 4,000 ft/mn,
  → Vertical acceleration: -0.8 to +2.8g,
- ***Horizontal gust*** (windshear)*:*
  20 m/s, 40kt,
  → Indicated airspeed variation:
  20 to 40kt,
  → Mach number variation: 0.03 to 0.05.

Figure 1

Severe turbulence associated with jetstream (polar front jetstream)



AIRCRAFT RESPONSE TO TURBULENCE UPSET

In turbulent conditions, the aircraft is naturally stable. This natural stability is further enhanced by the auto-pilot (AP) control laws. The AP has a built-in ability to cope with turbulence upset and, therefore, should be kept engaged (unless the AP action is considered to be unsatisfactory or leads to marked speed excursions) and should not be overriden during turbulence .

Figure 2 provides the synopsis of a typical sudden turbulence encounter, experienced during cruise on an A310 aircraft. Analyzing this event phase by phase provides an appreciation of the role of the three actors at play, the atmosphere, the aircraft and the pilot, throughout the encounter.

The flight data have been retrieved from the Digital Flight Data Recorder (DFDR). The vertical gust values have been derived by computation from the following data :

- true Angle of Attack (AoA), assessed by correction of local AoA data,
- pitch attitude,
- flight path angle relative to the ground, based on altitude history.

The initial conditions were as follows:

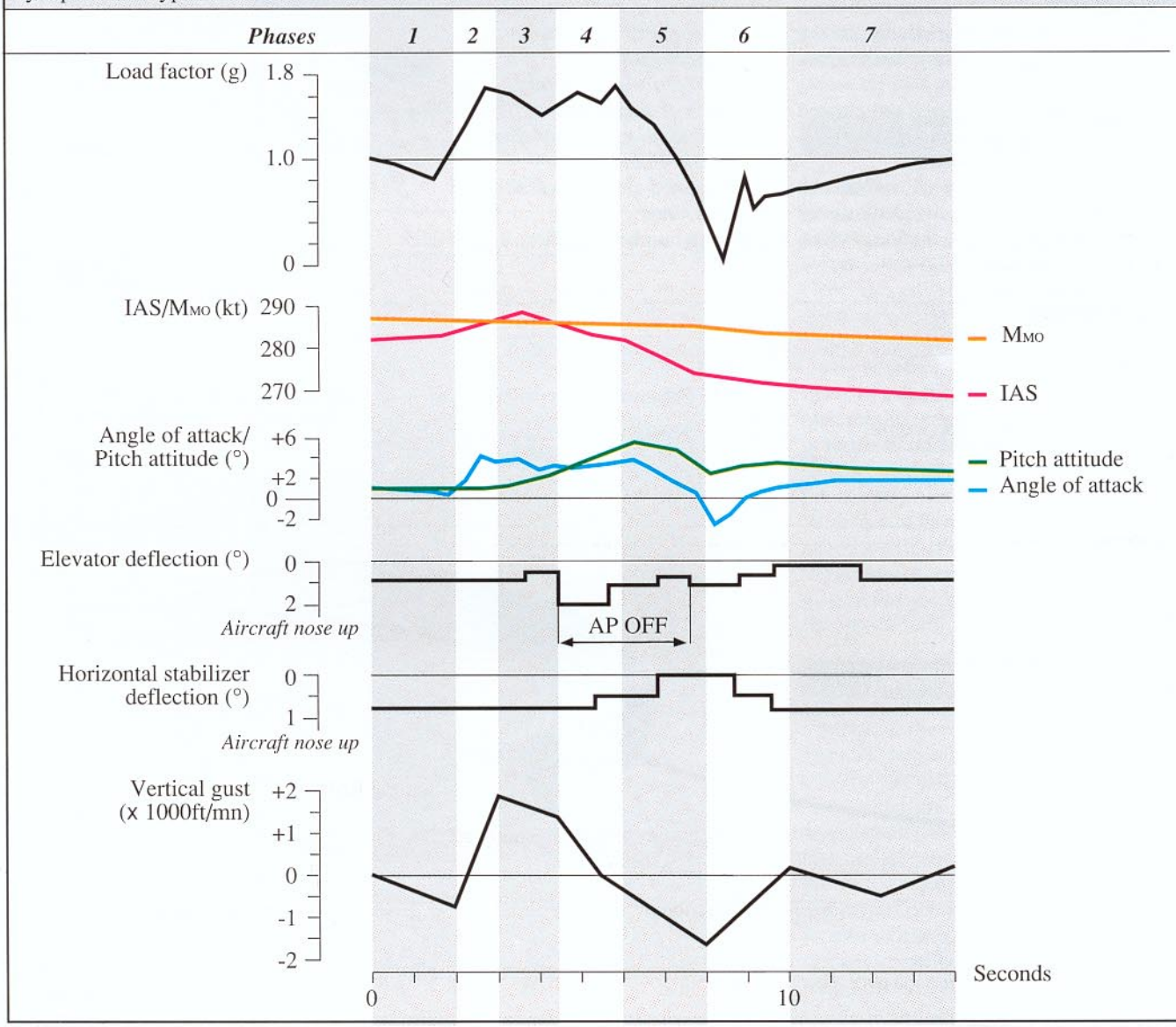
- flight level 350 (35,000ft),
- AP engaged in Command mode (CMD),
- Flight Management System (FMS) engaged in PROFILE and Navigation (NAV) modes,
- Mach 0.82,
- very low turbulence level ($\gamma < 0.05$ g).

This synopsis is typical and consistent with the analysis of many similar turbulence encounters. It clearly illustrates and explains the following aspects:

- the flight crew's manual pull-up order, leading to the AP disconnection, is a conceivable instinctive response to the perception of the sinking tendency as well as the overspeed condition;
- the large g-load factor variations are the result of the vertical gust effect and/or of the manual elevator orders, but are not the result of the AP activity in reaction to the gust.

Figure 2

Synopsis of a typical turbulence encounter



AUTO-PILOT DESIGN OBJECTIVES AND ENHANCEMENTS

The aircraft response to turbulence upset is a function of its aerodynamic and systems' design.

On the A310 and A300-600 the AP design objectives, in speed/altitude hold (SPD/ALT HLD) modes, are to maintain the selected targets as follows :

- speed: by immediate thrust variations,
- altitude: by pitch variations, with a vertical acceleration authority not exceeding ±0.2g.

The FMS design objectives, in PROFILE/NAV modes, are to maintain the speed and altitude targets with a reduced authority to maximize the passenger's comfort.

On the Honeywell FMS, this reduced authority is achieved as follows:

- speed: "soft speed" concept for reduced auto-throttle activity,
- altitude: pitch variations, with a vertical acceleration not exceeding ±0.05g.

On the Smiths FMS, a "soft altitude" concept fulfils the same objectives.

The Flight Augmentation Computer (FAC) and the Flight Control Computer (FCC) are the brain and heart of the aircraft system's response to turbulence.

Several changes summarized in Table 4 have been incorporated in the FAC to prevent the disconnection of the pitch trims and yaw dampers (and consequently of the auto-pilot) in turbulence, and to enhance the aircraft's response to

Table 4

Enhancement of FAC laws

	A310	*A300-600*
Increased acquisition rate for yaw rate and AoA data	P/N B352AAM3 Modification 7258 Airbus SB 22-2023	P/N B471AAM32 Modification 7720 Airbus SB 22-6012
Enhanced yaw behaviour (Fish tailing)	Not applicable to A310	P/N B471AAM3 Modification 8020 Airbus SB 22-6013
Improved α-trim law	P/N B471ABM3 Modification 8364 Airbus SB 22-2032	P/N B471AAM5 Modification 8834 Airbus SB 22-6014

Analysis phase by phase

Phase 1

- A first vertical gust is met (downdraft) which progressively reaches -700ft/mn.
- The angle of attack and the g-load factor decrease in response to the downdraft.
- The pitch attitude remains unchanged.
- No AP activity is observed. This conforms to the AP control law design which responds only to pitch or altitude variations.

Phase 2

- A second vertical gust (updraft) builds up, within one second, up to +2,000 ft/mn.
- This updraft results in an immediate increase of the angle of attack and, correspondingly, of the g-load factor.
- The pitch attitude starts to increase.
- A horizontal gust (horizontal wind-shear) associated with the large updraft leads to an MMO exceedance (Mach increases up to 0.85).

Phase 3

- The updraft starts to decay resulting in a corresponding decay of the angle of attack and g-load factor.
- The AP activity (elevator "aircraft nose down" order) is consistent with the pitch attitude increase (and the associated 100ft gain relative to the initial altitude).

Phase 4

- The updraft further settles. Perceiving the aircraft to be "sinking" as well as the overspeed condition, the pilot applies (quite understandably) a "nose up" elevator order. However, the corresponding force on the control column exceeds the preset threshold and results in the AP disconnection.
- As a result of the manual "nose up" elevator input, the pitch attitude, the angle of attack and - correspondingly - the g-load factor increase again.
- The pitch attitude continuing increase is counteracted by the horizontal stabilizer "aircraft nose down" deflection (angle of attack protection, known as the α-trim function).

Phase 5

- The updraft completely settles and turns into a downdraft reaching -1,600 ft/mn.
- The angle of attack and g-load factor decrease in response to the downdraft.
- Under the combined effect of the downdraft and the "aircraft nose down" trimming (α-trim) the g-load factor reaches temporarily 0 g.
- The AP is re-engaged, although the flight parameters are still significantly affected.

Phase 6

- The elevator order and horizontal stabilizer deflection return to normal values, while the downdraft starts to settle.

Phase 7

- The turbulence encounter is over, all flight parameters return to stabilized values.

Table 5		
Enhancement of FCC laws		
	A310	*A300-600*
ALT HLD mode and AP connection time delay	P/N B470ABM2 Modification 10402 Airbus SB 22-2036	P/N B470ABM2 Modification 10403 Airbus SB 22-6021

and recovery from a turbulence upset. After incorporating these changes, no AP disconnection in turbulence has been observed, except those resulting from a force being applied by the flight crew on the control column.

The response of the AP in turbulence has been also enhanced by increasing the rate of the altitude recovery in ALT HLD mode and by adding a time delay for the AP disconnection by force on the control column. These improvements have been incorporated in the most recent FCC standard (Table 5).

On the A320 and subsequent fly-by-wire (FBW) models, the in-service experience has confirmed how well the FBW philosophy is ideally suited to enhance the aircraft behaviour in turbulent conditions. The benefit of FBW is particularly visible in manual flight in "stick neutral" condition. The characteristics of the FBW control laws (in terms of response time and rate) are such that the aircraft will stabilize quite rapidly whereas a conventional aircraft would oscillate in the same conditions.

Flight crew procedures

The procedures for *Flight in Severe Turbulence* published in the *Procedures and Techniques* chapter of the FCOM for the A300/A310/A300-600 aircraft, Supplementary Techniques chapter for the A320/A321/A330/A340 aircraft) are consistent for all aircraft models regarding the following recommendations :

- disconnect auto-throttle (A/THR) to prevent auto-throttle activity,
- keep AP engaged.

On the A310 and A300-600, the AP should be kept in CMD but a manual reversion should be made from PROFILE to ALT HLD in cruise, or Level Change (LVL CH) in climb or descent, to take benefit of the full AP authority. This latter recommendation should be considered not only upon entering a turbulent area but also as a preventive action whenever there is evidence that severe turbulence is likely to be encountered.

Using the AP in SPD/ALT HLD modes, instead of PROFILE, will also help to prevent the occurrence of a VMO / MMO exceedance condition.

The Control Wheel Steering (CWS) mode should not be used. Because of the light stick forces, resulting from the absence of artificial feel and pitch feedback in this mode, and of the availability of the auto-trim (the CWS mode being an AP mode), the CWS mode is very sensitive and not appropriate for flight in severe turbulence.

No attempt should be made to resist or override the AP action by applying a force on the control column. This would result in the AP disconnection and further upset of the flightpath.

It is worth stressing that the g-loads felt during turbulence are mainly due to the gusts and not due to the AP activity.

In case of an overspeed condition, the procedure for VMO / MMO exceedance recovery should be followed. Using the speedbrakes may be considered but their extension may further amplify the g-load variations.

Only if the AP actions are considered unsatisfactory or if a marked exceedance of VMO / MMO is experienced, should AP be disconnected and the aircraft be flown manually with smooth control inputs.

Cabin crew procedures

An FAA study reveals that most of the serious injuries affecting passengers, walking in the cabin or seated unrestrained by their seat belts, have been experienced after an announcement requiring the passengers to return to their seats and/or fasten their seat belts.

Flight attendants take the greater toll in serious injuries as their crew duties require them to secure cabin and galley equipment and check passengers before seating and securing themselves.

Without formally considering leaving the *Fasten Seat Belt* sign ON for the entire flight (which would not fulfil the inten-ded purpose), the authorities are considering stricter rules to enforce the compliance with the cabin announcements and signs. In the meantime, the operators could (or should) lead the way in developing stricter recommendations and procedures to help flight attendants enforce cabin announcements and signs.

CONCLUSION

Although areas and severity of turbulence can be quite accurately forecast, unheralded turbulence encounters cannot be totally avoided. Whenever applicable, the product improvements, developed to enhance the aircraft behaviour in turbulence, should be considered for incorporation at the earliest convenient opportunity. The particular nature of flight in severe turbulence and its possible consequences should be highlighted (together with the associated procedures) to flight crews and cabin crews as part of a dedicated awareness of turbulence in general training programmes. By adhering to the above recommendations, a turbulence encounter should remain a normal play but by no means become a thriller.