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The Accuracy Verification of the Static Pressure for the RVSM Compliance of Aircraft

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Braunschweig, 10-Jan-03

1 Introduction

Aeroflight Servicegesellschaft mbH offers a worldwide service to achieve RVSM (Reduced Vertical Separation Minima) airworthiness for all aircraft. RVSM means the reduction of the vertical distance between two aircraft from 2,000 ft to 1,000 ft in the altitude range between 29,000 ft and 41,000 ft. Every aircraft which flies in the RVSM airspace must have a certification about the accuracy of its barometric altitude measurement and height keeping system. The newly constructed aircraft are prepared at the outset for achieving all necessary accuracy features. Afore designed aircraft possibly need a suitable sensor equipment. In detail the equipment required for a RVSM compliant aircraft consists of:

- two independent altitude measurement systems that meet the system error requirements,
- one automatic altitude control system that controls the aircraft altitude within ± 20 m (± 65 ft),
- one altitude alert system that alerts to altitude changes of ± 90 m (± 300 ft),
- one secondary surveillance radar (SSR) altitude reporting transponder,
- an RVSM compliant avionics configuration.

For the individual approvals the sum of the mean error contributions of the altitude measurement systems plus the 3-σ-values has to remain inside the limits given by ± 160 ft and ± 200 ft for basic and full flight envelope respectively (see [1]).

To achieve the RVSM certification for an aircraft, Aeroflight provides flight test support including development of flight test plan (FTP), the co-ordination of the FTP approval with any certification authority, the provision of a flight test engineer to operate the flight test instrumentation and to monitor the flight test. After the flight test is complete Aeroflight provides the data processing, analysis and reports to gain the RVSM STC with the aviation authorities.

2 The Procedure for Individual Aircraft Certification - The Non-Group Approval -

2.1 Primary Certification

Aeroflight's method is based on all applicable, currently valid European, American, and international guidelines and requirements, explicitly:

- 14 CFR Part 91, Appendix G,
- FAA Document 91 - RVSM (Interim Guidance Material on the Approval of Operators/Aircraft for RVSM Operations),
- JAR OPS 1.241 and 1.872, and
- JAA Temporary Guidance Leaflet No. 6 Rev. 1.

2.1.1 Avionics Evaluation

As already mentioned, the avionics installed in the aircraft must meet certain minimum requirements. If the avionics (air data computer, altitude indicator, altitude alerter and auto pilot) do not fulfil these requirements some portions of this avionics or the entire set need to be replaced.

So the first step in an RVSM certification project is the evaluation of the aircraft avionics system with respect to their RVSM capability. If an avionics modification is required, Aeroflight will provide a recommendation on hardware for the upgrade. Aeroflight can coordinate the aircraft modification either through the owner/operator's maintenance, another design organisation in the country of registry or through Aeroflight's organisation.

Once, the aircraft's hardware is compliant with the requirements of RVSM, and the customer has decided to proceed with the RVSM certification program, a suitable certification program plan is developed.

2.1.2 The RVSM Certification Procedure

The Preparation:

For the calibration different well calibrated pressure transducers are connected to the pitot-static-system of the aircraft. One additional transducer measures the static pressure of the reference system - a trailing cone (see Fig. 1). This is a resistance body at the end of a rod to strengthen it. Close to the end there are static pressure ports in the rod, enabling the determination of the static pressure outside the area disturbed by the aircraft. This reference static line has to be fed into the cabin through the pressurized body.

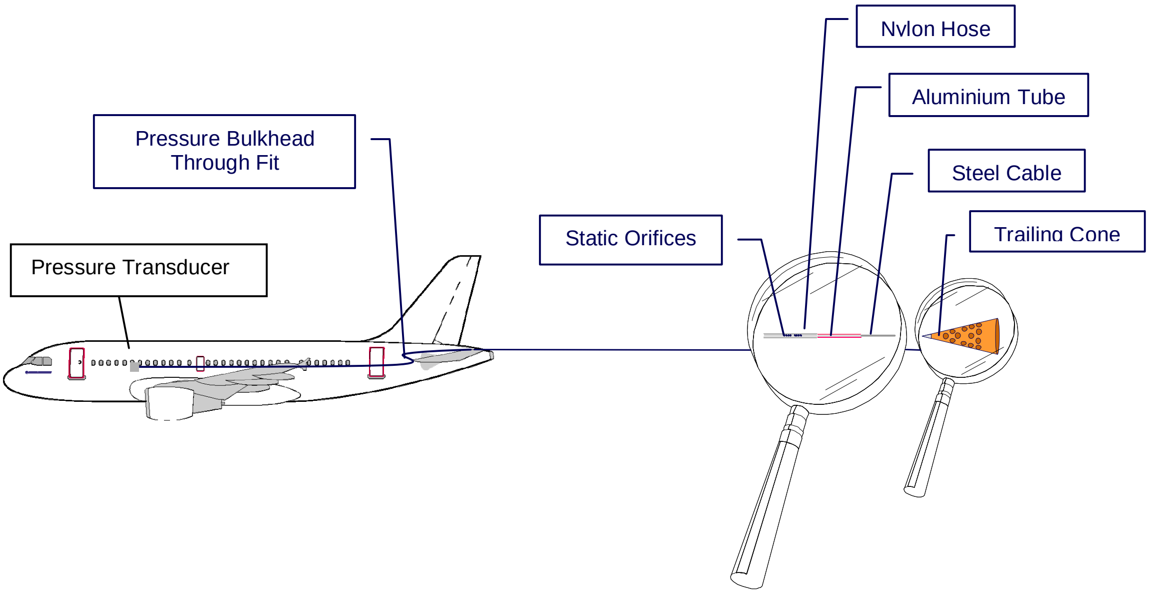

Fig. 1: The trailing cone configuration.

The preparation of this flight test starts with the determination of the flight envelope (as depicted in the following diagram) required in the RVSM airspace. The so-called weight-over-pressure ratio, gross weight / (p_s / p_0), is plotted versus the Mach number (see Fig. 2). The borders are defined as follows:

Top: maximum possible weight at FL 410,
Bottom: minimum weight at FL 290,
Right: maximum operating Mach number or maximum cruise thrust,
Left: holding speed or manoeuvre speed.

The suitable points are selected within this flight envelope at different speeds and weight over pressure ratio to cover the whole area. In the diagram, these flight test points are shown as red dots.

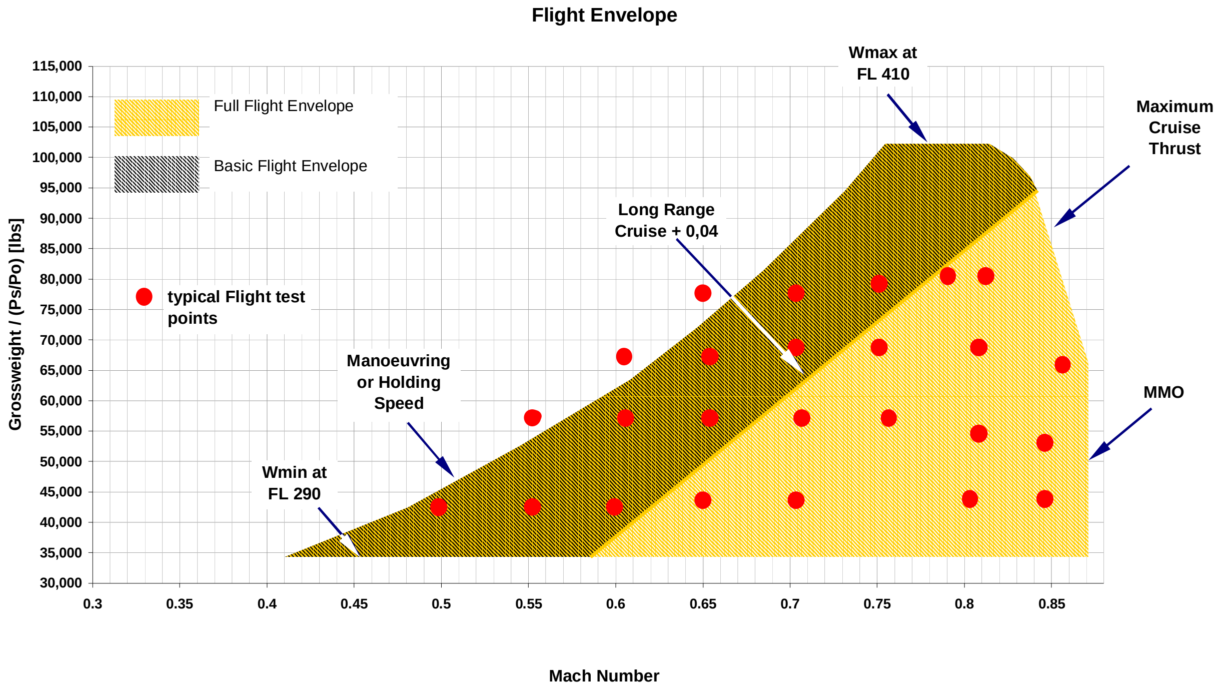

Fig. 2: The typical flight envelope of a business jet in the general aviation. The indicated points represent the targeted flight parameter constellations for the test procedure.

p_s static pressure

p_0 standard pressure on ground (1013.25 hPa)

One or two days are required for the installation of the flight test equipment. It consists of the pressure transducer box, the data acquisition system, and the trailing cone. After the installation, a leak check is performed. For the flight test activities, the aircraft certification has to be set by the operator to the status “Experimental”.

The Flight Activities:

The first short flight is for cone calibration, consisting of several low-level fly-by maneuvers at different speeds. The main flight test itself takes about four hours. At each test point, the aircraft has to be stabilized for at least one minute while all pressure data is recorded. The autopilot height-keeping performance is checked on 10-minute legs as well as during acceleration and deceleration under autopilot operation. At the end of each test series at one altitude, a climb or descend is initiated while the altitude alert function is recorded.

The deinstallation of the measurement system takes another day. Hence, under ideal conditions, three days are required in total for the flight test activities.

The data evaluation:

The reference pressure is compared with the static pressure raw data of the pilot and co-pilot side. The result comes out with static pressure correction functions (SSE, see Fig. 3) to be implemented in the air-data computers for both sides, pilot and co-pilot. As illustrated in the following diagram, the correction mainly depends on the air speed and less on the weight-over-pressure ratio W / δ (with: W = gross weight, and $\delta = p_s / p_0$).

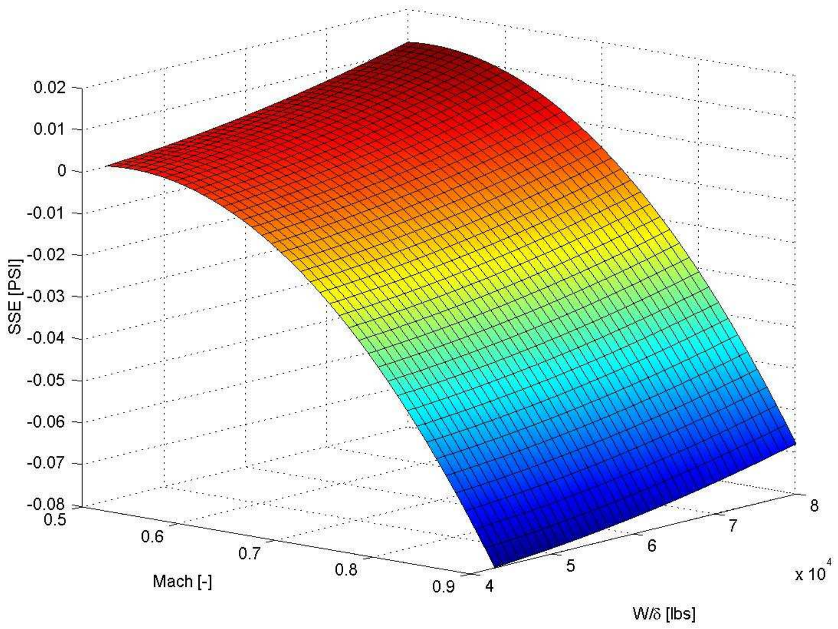

Fig 3: A typical distribution of pressure correction values.

SSE [PSI]: static source error,
Mach: Mach number,
W / δ [lbs] : Weight over pressure-ratio.

2.1.3 Preparation for Aerodynamic Effects of Long-Term Shape Mutations

For the primary certification an initial survey of the skin shape around the static port is performed. It is necessary to get the status of the local shape structures. For this purpose, Aeroflight Servicegesellschaft uses a photogrammetric measurement system (see Fig. 4).

Fig. 4: Photogrammetric system to resolve surface bulge structures of 0.02 mm if an area of 1 x 1 m is captured.

These skin survey activities don't have any influence on the estimation of errors for the primary certification. But it is important for having a basic data set to be able to detect any shape mutation for the further on sustaining of the certification. Especially affected are those kinds of pressure ports being integrated inside the fuselage. The L-shape probes mounted in a distance to the aircraft body are less concerned provided that the probe itself is successfully kept in its original shape.

2.2 Continued Airworthiness

Normally, no further test flight activities are required to maintain the RVSM airworthiness of the aircraft. The regular checks of

- the functionality of avionics hardware, including the auto-pilot and Air Data Computers,
- the pressure transducer calibrations, and
- the the pitot-static plumbing tightness

are needed. Addtionally, the RVSM critical fuselage region must be inspected for obvious major damages or deformations before every flight because already very small alterations in this area have a tremendous influence on the static source error and therefore on the barometric altitude. Even a non-homogenous paint distribution in this region or paint ridges are not acceptable. Furthermore the static plates must be free of paint and any obvious damages. The static ports itself must be inspected for foreign objects in the port orifices, corrosion, elongations, deformations and obstructions.

After every modification of the RVSM critical fuselage region as well as every 24 months on a periodically base, the status of the skin waviness has to be verified by the skin shape measurement as explained in the preceding chapter.

The pressure signal at the static ports is an overlay of mainly the ambient pressure, and the aerodynamic perturbation effects. The length scales of these flow structures are in the range between

- the complete aircraft expansion, and
- the boundary-layer thickness
  over the fuselage skin at the location of the pressure port.

The smaller the scale of any occurring object the smaller has to be its distance to the static port location for any significant impact.

The aerodynamic part of the procedure for the continued airworthiness normally remains at the check for any shape mutation in the vicinity of the static port. The comparison between the old and the new surface structure images may come out with differences. These structure elements could result in pressure perturbations at the static port location. Roughly spoken, this perturbation depends on the following geometrical features of the structure and its location with respect to the pressure port (schematic explanation, see Fig. 5):

- the length scale (i.e. wave length **λ**),
- the elevation (or amplitude) **A**, and
- the distance **D** to the static port.

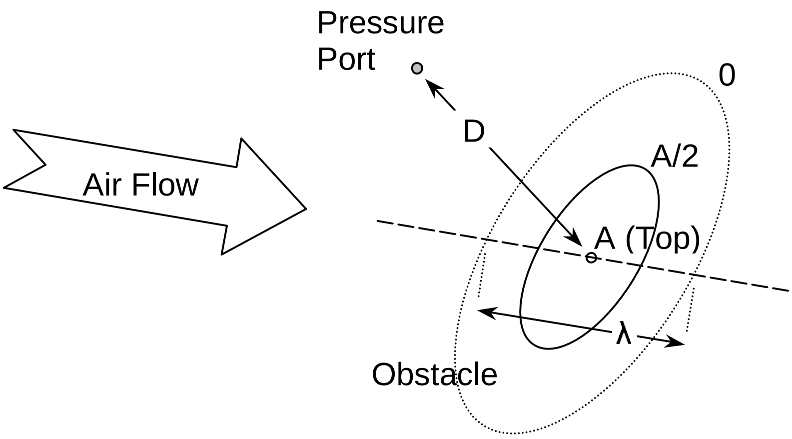

Fig. 5: Schematic view about the utilized parameters for the estimations of the static pressure error.

The most simple approach for the estimation of the pressure perturbation finally leads to a suitable worst-case consideration:

- The structure is effectively taken as being a two-dimensional object (a ridge) with the length scale (wavelength **λ**) in its cross section parallel to the flow direction.
- The distance **D** is applied in the calculation as being always situated in the same streamline as the pressure port.
- The air flow is frictionless but compressible.
- The magnitude of the obstacles elevation **A** (positive as well as negative) has to be small compared to the length scale **λ**.

In reality, the perturbation effects of three-dimensional surface structures not being in the same streamline with the pressure port are always smaller as those under the conditions listed above.

The calculation uses the thin-airfoil theory [2]. It is initially based on the assumption of a non-compressible medium and a potential flow. Anyhow, the normally negligible compressibility effects of the air are taken into account because they have to be added to the non-compressible flow effects.

Table 1 shows the magnitude of the resulting altitude errors on conditions of the International Standard Atmosphere at FL 410 and at a Mach number of 0.85 in the case of having the pressure port in the middle of the obstacle. A camber elevation of 1 mm with a wave length scale of 20 cm causes a barometric altitude error of more than 400 ft. But even a length scale of 1 m results with nearly 10 ft at a fuselage surface elevation of 0.1 mm.

A (mm)	Error of the Barometric Altitude (ft)			
1	846	422	169	84
0.5	422	211	84	42
0.2	169	84	34	17
0.1	84	42	17	8
0.05	42	21	8	4
0.02	17	8	3	2
λ (m)	0.1	0.2	0.5	1

Tab. 1: The error of the barometric altitude depending on the cross section length and the height extension of a two-dimensional fuselage obstacle.
The conditions are:
- pressure port in the middle of the obstacle (**D** = 0),
- FL 410 in the International Standard Atmosphere,
- Mach 0.85 .

Table 2 gives an impression about the altitude error in the pressure measurement in a distance **D**, normalized with the wavelength **λ**, to the obstacle. Note the error's zero-crossing between 0.2 and 0.5. At a distance of one wavelength there is still 5 % of the maximum error on top of the object. This table gives only an exemplary explanation of the flow effects across a two-dimensional perturbation structure. Each three-dimensional obstacle with similar values of the normalized height **A / λ** results with an altitude error of smaller magnitude.

A / λ					Error of the Barometric Altitude (ft)		
0.01	846	527	113	-101	-44	-13	
0.001	84	53	11	-10	-4	-1.3	
0.0001	8	5	1.1	-1.0	-0,4	-0.1	
0.00001	0.8	0.5	0.1	-0.1	-0.04	-0.01	
	0	0.1	0.2	0.5	1.0	2.0	**D / λ**

Tab. 2: The error of the barometric altitude depending on
- **D**, the distance between the obstacle and the pressure port, and
- **A**, the obstacle's top elevation (here: positive)

of a mathematically simple two-dimensional fuselage obstacle (inverse polynomial cross section, see also [3]), both normalized with its wavelength across the ridge.
The conditions are:
- FL 410 in the International Standard Atmosphere,
- Mach 0.85 .

The values shown in the tables are to be interpreted as worst case results. If this value exceeds the RVSM error limits, additional test flight activities are required. The really expected amount of perturbation will be definitely below these calculated values.

3 Perspective

Once, the certification of an aircraft is realized, the sustaining of this status is manageable. Any resumption of the test flight procedures has to be kept at a low probability. Aeroflight is able to support this state even in the case of moderate and eventually non-critical shape mutations around the static ports. The presumptions of the calculations are designed to result with the very worst case of error constellation. Hence, there is some chance to avoid additional check flight efforts.

4 References

[1] JAA Administrative & Guidance Material Section One: General Part 3: Temporary Guidance Leaflets (TGL 6), Rev. 1

[2] Krishnamurty Karamcheti, "Principles of Ideal-Fluid Aerodynamics",John Wiley and Sons, New York, 1966

[3] Hoff: "Ein analytisches Verfahren zur Bestimmung der mittleren horizontalen Windgeschwindigkeiten über zweidimensionalen Hügeln", Berichte des Instituts für Meteorologie und Klimatologie, University of Hannover, 1987