WE VIBRATE - RE-PUSHING THE ENVELOPE (G550 HALO TGI FLIGHT TESTING)

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Abstract: DLR's High Altitude and Long Range Research Aircraft (HALO), a heavily modified Gulfstream G550 (GV-SP), is a high-performance platform. The baseline HALO modifications of the G550 enable DLR`s and partnering scientists to equip the aircraft with various pieces of hardware for probing and analyzing the surrounding atmosphere "in-situ". A key role for in-situ measurements plays DLR's standard Trace Gas Inlet (TGI), a structure that enables probing the atmosphere outside the aircraft's boundary layer.

Due to the new and previously untested design of the TGIs, the high number of installable TGIs and their design derivatives (~ 20 pieces over the whole fuselage) and the resulting number of combinations, DLR chose a careful build-up approach to first assess the two baseline TGI designs in flight at different fuselage positions, followed by a step-by-step testing of multiple combinations of TGI designs, design derivatives and fuselage positions, slowly increasing the complexity of the setup.

The achieved main goal of the flight tests was certification of the inlets to supplemental type certificate (STC) status.

The flight test program encountered vibration issues during the build-up procedure resulting in the need of close vibration monitoring and a partly redesign of the TGIs trailing edge.

The extensive testing also resulted in the development of a simple vibration measuring technique and an efficiency increase of the flight test methods.

1 INTRODUCTION

This paper highlights a set of results of different regimes of the flight test program that ultimately led to the certification of a scientific modification for DLR's Gulfstream G550 HALO aircraft, the standard Trace Gas Inlet, TGI. It touches the developmental flight test phase as well as the certification flight test phase.

The purpose of the flight tests was to determine possible influences of the TGI to the A/C's flight characteristics, performance and structure. The tests included developmental test phases to open the flight envelope of the baseline G550 HALO for flights with the aircraft equipped with one or more TGIs. It also incorporated certification test phases to certify the modified aircraft against JAR25 change 15.

The tested modification, the TGI, is a "clean sheet" design that had to comply with various demands from the scientific community for whom it had been designed as well as demands of the certification authority, the Luftfahrtbundesamt (LBA). The most prominent demands were collecting air samples outside the A/C's boundary layer and the TGIs bird strike behaviour. To satisfy the boundary layer demand, two versions of the TGI were designed: a tall version, TGI-430 and a short version, TGI-320 (Figure 4). The reason was the result of a CFD analysis of the A/C's boundary layer. A major factor in the design of the TGI was its ability to fit the G550 HALOs provisions (Figure 3). Those provisions are highly similar to those of another atmospheric research aircraft, a Gulfstream GV, operated by NCAR in the USA. This aircraft was built a few years before and the design of the provisions was adopted.

Figure 1: G550 HALO with inlet probes

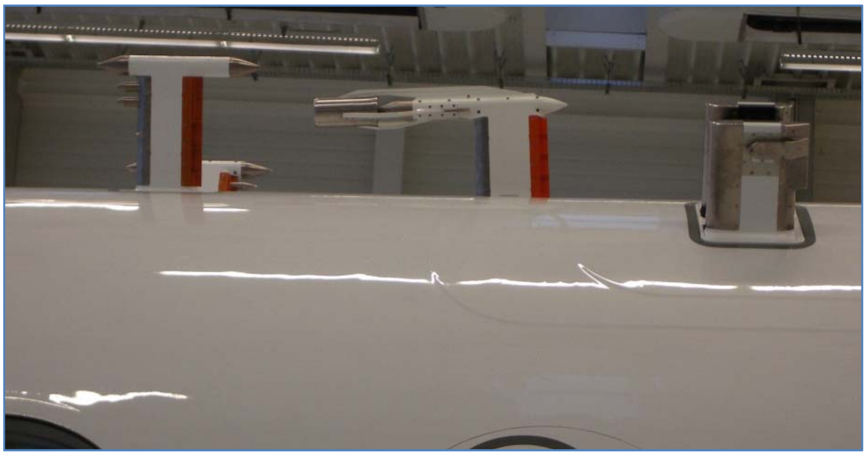

Figure 2: TGI (left); Design derivative CVI (middle); HAI (right)

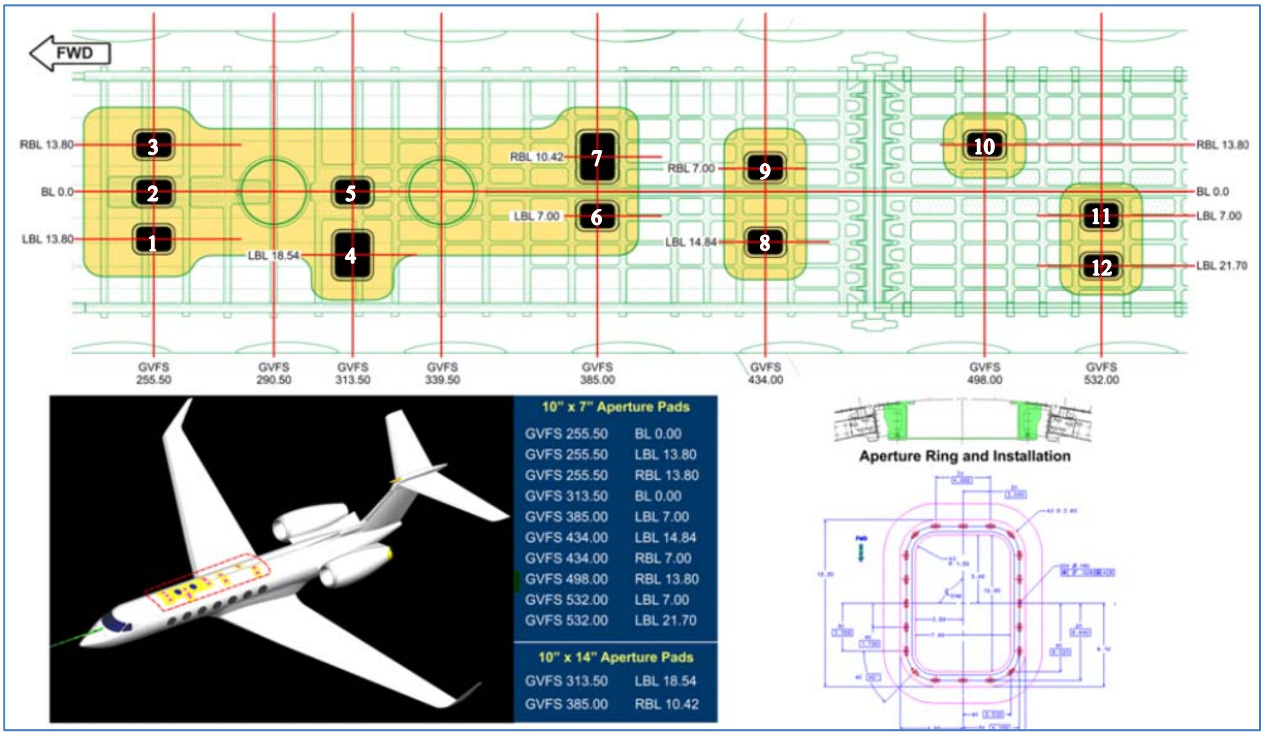

Figure 3: Mounting provisions "Aperture Plates" for the TGI [3]

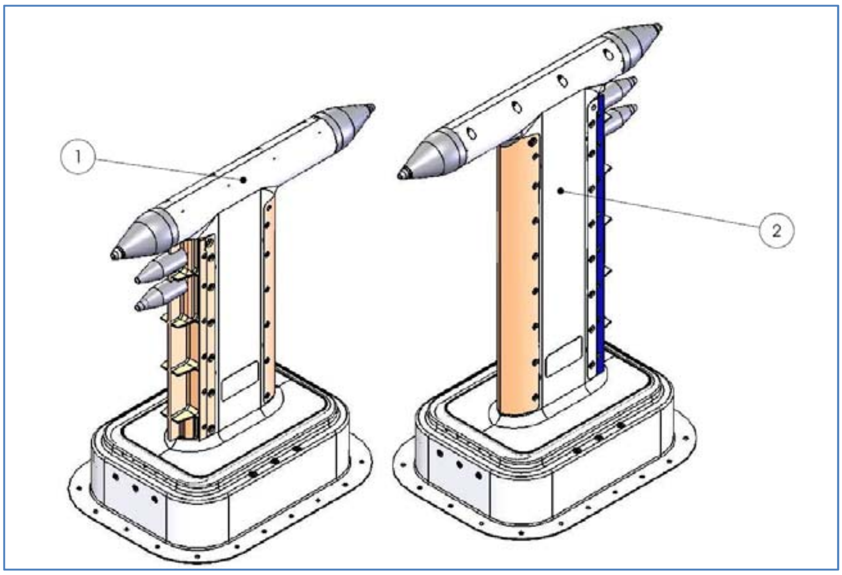

Figure 4: TGI 320 (#1); TGI 430 (#2)

The tested aircraft was a Gulfstream G550 with the "High Altitude and Long Range" modification. It is based on a Gulfstream G550 (GV-SP) ultra-long range business jet which itself is an upgrade to the Gulfstream GV aircraft. The G550 comprises an upgraded Honeywell avionic system and aerodynamic improvements with respect to the GV [1]. It is equipped with two Rolls Royce Deutschland BR700-710C4-11 turbofan engines, each delivering a max. continuous static thrust of 64 277N (14 450 lbs) at sea level. Its maximum operating altitude is 15 545m (51 000ft) [2] and maximum velocity is Ma .885.
HALO is equipped with a high quality basic atmospheric data acquisition system.
The flight control system is a hydraulically boosted reversible direct flight control.

Instrumentation of the TGIs was done by simple accelerometers connected to the already available atmospheric basic data measurement system. The TGIs were also closely monitored for audible and tactile vibrations.

For general flight test data gathering, the atmospheric basic data measurement's data in conjunction with an L3 Micro Quick Access Recorder and hand held data provided the necessary database to accomplish the task sufficiently.

2 TGI FLIGHT TESTING HISTORY

2.1 Experimental Phase

The "experimental phase" was part of the classic development flight test phase, but for clarification purposes it has been detached from the development phase chapter.
Flight testing of the TGI began in August 2010 with testing a single TGI-430 of the first design on an aft position (ApT-9 at GVFS 434.00/RBL 8.3), considering this setup to be aeroelastically worse than flying a short TGI-320 on a forward position on the upper side of the fuselage (Figures 5 & 6). A preceding impulse hammer test helped to focus on critical eigenfrequencies.
The idea was to start initial testing with a single TGI, confirm the baseline aircrafts flight envelope to still be valid, slowly increase the number of inlets, types and combinations and then move on to the certification phase to answer all applicable paragraphs of the regulations.
At lower altitudes (up to FL150), the flight envelope could be expanded with no problems whatsoever. Climbing into the higher altitude regimes of thinner air and compressibility effects, the TGI started to show audible and measurable vibration, starting at Ma .7 in FL300 during side slip manoeuvres [4]. Although being a thought-of possibility, it seemed to be a bit of a surprise to the test team, as the very stiff design seemed to promote a rather uninteresting behaviour concerning the "felt rigidity" of the inlet. For further testing, a limit g-load on the tip of the TGI was set, measured by a unique accelerometer setup, see chapter 3.

Figure 5: TGI original design

Figure 6: first test flight installation of TGI-430

It was agreed that the vibrations had to have their source in pressure effects due to the rather blunt aerodynamic shape of the TGI, supported by a brief aerodynamic calculation, see Figure 7 [5]. Therefore a solution to influence the TGIs boundary layer was investigated; the easiest and quickest available to be classic adhesive turbulator tape, being a standard on most current sailplane wing designs (Figure 8).

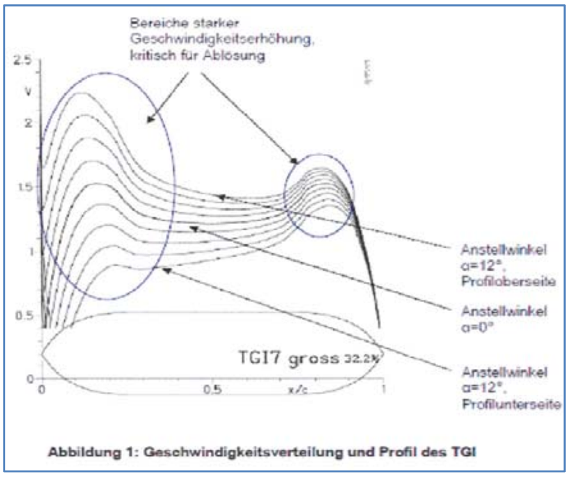

Figure 7: simple 2D CFD analysis

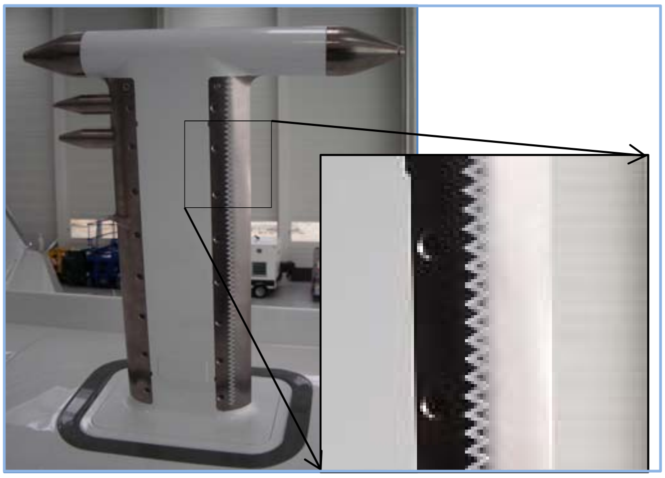

Figure 8: TGI /w turbulator tape

Testing a TGI-430 on the aft ApT-9 with the turbulator tape was successful trough the full envelope up to M_{DF} [6].
As the turbulator tape is designed for sailplanes and their respective flight regime, a permanent solution was needed as the adhesion of the tape worked only for a limited flight time. With only very limited research resources available for theoretical research and narrow time slots, flight testing was the only research method available to proof various designs for boundary layer influence.
During the test campaign, Bird Strike issues were brought up and the TGI's interface to the aircraft structure had to be redesigned [7]. This led to repeated testing of the TGI-430 at ApT-9 with turbulator tape. The test was successful throughout the flight envelope [8].
Machined grooves close to the leading edge instead of the tape proved unsuccessful (vibrations at FL280/296KCAS)[9], returning to testing with the tape, now with the TGI-430 switched to ApT-11, an aft most position. Surprisingly the TGI showed the same vibration issues with the turbulator tape (at FL280/Ma.73; tape still being intact after landing) at that position [10] as before on ApT-9 *without* the tape.
Testing the shorter and therefore stiffer TGI-320 variant on a forward position ApT-3 with the turbulator tape stuck on showed a similar result: inacceptable vibration at Ma.78 at FL280 [11].
Repeated testing of the TGI-430 with stuck on tape on the previous ApT-9 led to another surprise: now the TGI showed the vibrations that had vanished before (FL280 / Ma.78) [12][13], after switching from a smooth to a tape-influenced leading edge surface. A configuration change of the TGI had occurred compared to the successful flight test of [8]: due to bird strike demands, a set of bolts had been replaced by hollow bolts.
The whole vibration problematic led to the suggestion of using more prominent turbulators: vanes and spikes fabricated by rapid prototyped plastic and fit into a machined slot of the leading / trailing edges (Figures 9 & 10).

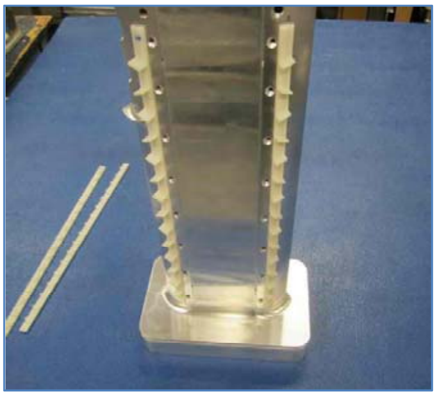

Figure 9: turbulator vanes

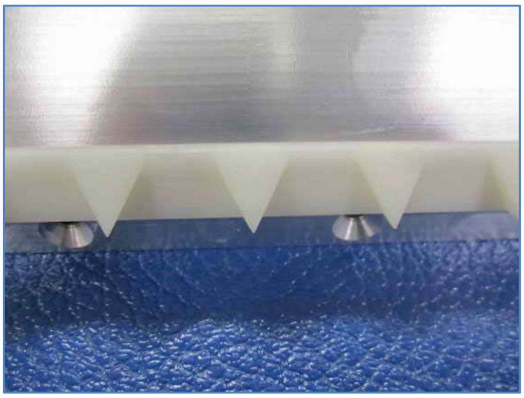

Figure 10: spikes

Testing continued with the turbulator vanes on the TGI-430 on ApT-9. The flight test engineers on that flight noticed high vibrations in the 400Hz regime in FL150, exceeding the postulated limit at 220KCAS. The flight test was cancelled [14]. Testing the spikes went similar, 400Hz vibrations exceeding the limit at FL150/240KCAS [15]. Eventually all vibration measurements show high peaks in starting at the 400Hz range, increasing with frequency. Those were ultimately attributed to measurement noise.
Repeated testing of the TGI-430 on ApT-9 with the turbulator tape showed the TGI to be free of vibration in FL280 up to the tested speed of Ma.89[16]. Testing the TGI-430 with tape again on ApT-11 led to the previous result of unacceptable vibrations (FL280/Ma.74)[17]. Repeating the test of TGI-430 on ApT-11, this time with the turbulator tape stuck on the leading and trailing edges, led to the same inacceptable results (FL280/Ma.74)[18].
Testing a TGI-320 with turbulator tape on ApT-8 showed a completely different result: no vibration throughout the tested envelope up to Ma.92/FL430 [19]. Therefore the short TGI-320 version with turbulator tape was tested on ApT-11. Significant vibrations were encountered at FL280/Ma.78[20]. So, a test with the TGI-320 with turbulator tape on the neighbouring ApT-10 was conducted. Again, without success (FL280/Ma.8). Parallel to the last few flight tests, more complex aerodynamic calculations via CFD analysis were undertaken [22], showing the build-up of a Kármán vortex street behind an oscillating supersonic flow pressure field (Figures 11 & 12).

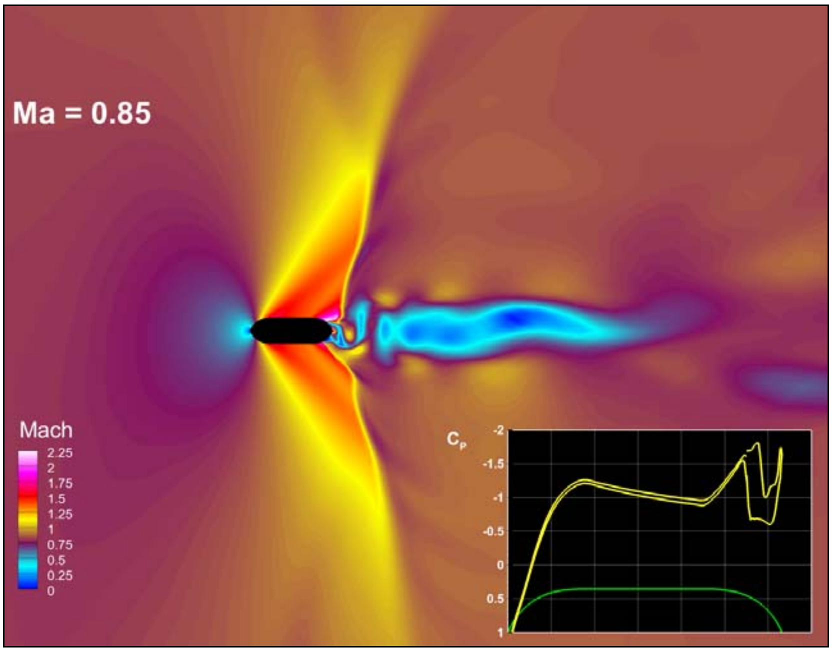

Figure 11: Oscillating pressure fields, CFD analysis [22]


Figure 12: Kármán vortex street [24]

The result was a design change of the trailing edge for the TGIs, followed by flight tests [23]. Three versions of a so-called “splitter plate” were machined to separate the airflow and stop the oscillating pressure fields from exciting vibrations of the TGI (Figure 13).

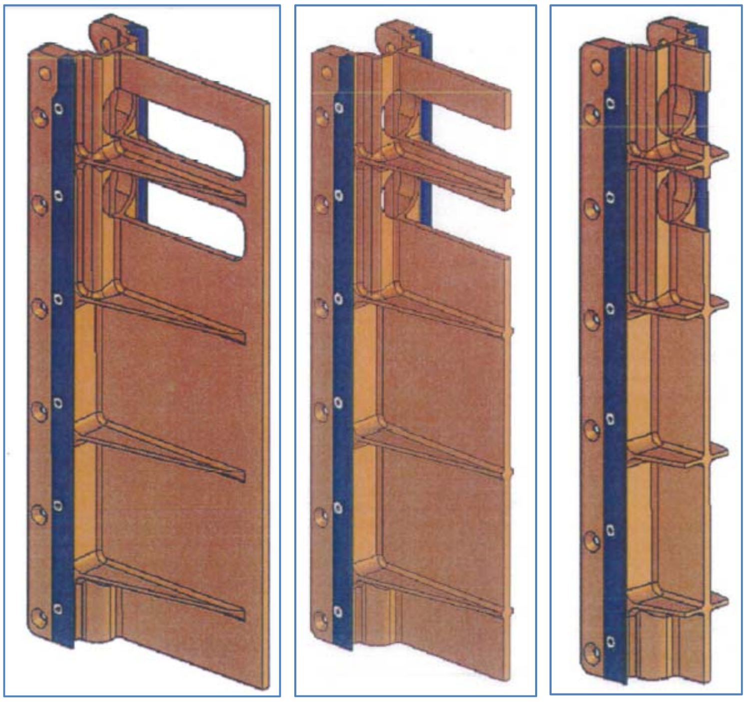

Figure 13: from left to right: Splitter Plate SP1; Splitter Plate SP2; Splitter Plate SP3 [24]

Testing the Splitter Plate SP1 on a TGI-320 was unsuccessful due to a quick vibrational build-up [26]. Testing the Splitter Plate SP2 was skipped and testing continued with the Splitter Plate SP-3 on the TGI-320 at ApT-3. This was done with success. The vibrations of the TGI had not vanished, but the Splitter Plate SP3 proved useful to keep the vibrations well below the limit [27], leading to the serious Development Phase(s).

2.2 Development Phase

After the experimental phase, that helped solving the basic technical issues of the TGI from an engineering point of view, the development phase - or better: phases - followed. A development phase is hereby defined as the set of flight tests that is needed to re-open the flight envelope (Figure 14) with a previously untested A/C setup.
The development phases interchanged with the certification phases for each new setup of the TGI Positions.
The initial development phases included taxi tests in different A/C configurations for all new TGI setups. With increasing experience and confidence the amount of taxi tests was reduced and finally waived.
The flight tests followed a build-up procedure (Figure 15) and were performed in restricted (TRA) airspace:

1. Assessment of a safe flight envelope for landing configuration after take off
2. Testing of the corner points of the flight envelope, slowly approaching the limits by pausing the acceleration and closely monitoring the vibration behaviour of the TGI

A limit was testing of the stall speeds with the pusher of the aircraft defining the stall. No aerodynamic stall testing was conducted.
An Envelope Expansion Procedure (EEP) including tests for vibration, buffet, flutter up to V_{DF} / M_{DF} was conducted, with V_{DF} = 368KCAS in 15000ft PA and M_{DF} = M.92 in 33000ft PA. The CG was at an aft position for those tests.
Manoeuvrability, static lateral and directional stability, lateral and directional control, longitudinal stability and longitudinal control were tested.

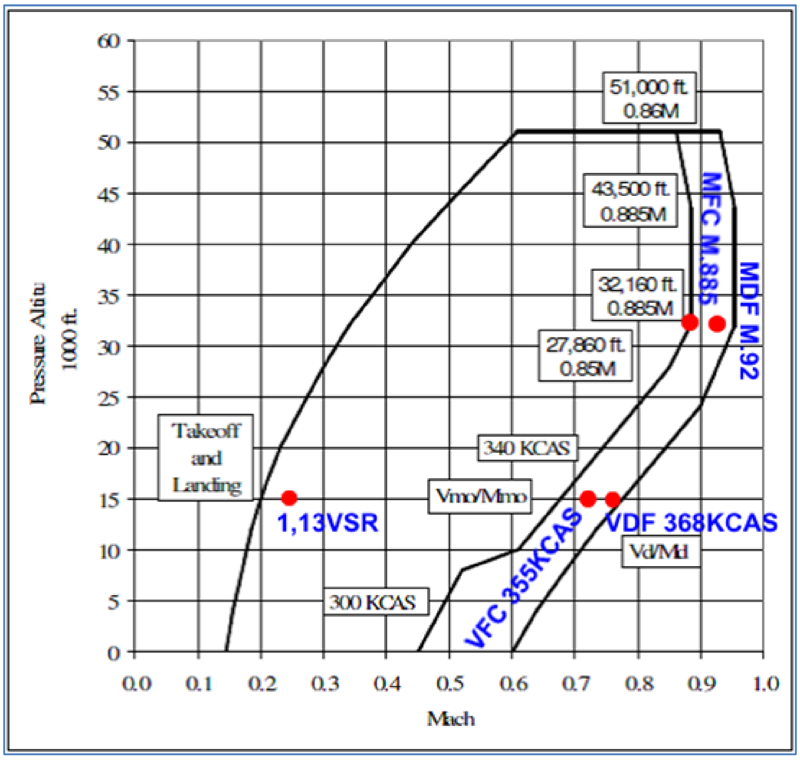

Figure 14: Build-up procedure: G550 flight envelope – certification test points

Step	Overall Quantity of Inlets	Aperture Plate / Viewport	Type of Inlet	Other external Modifications
1	1	ApT-3	TGI-320	
2	1	ApT-6	TGI-320	
3	1	ApT-10	TGI-320	
4	1	ApT-11	TGI-320	
5	2	ApT-3 / ApT-6	TGI-320	
6	3	ApT-3 / ApT-6	TGI-320	
		ApT-9	TGI-430	
7	3	ApT-1 / ApT-3	TGI-320	
		ApT-9	TGI-430	
8	1	ApT-10	TGI-430	
9	1	ApT-11	TGI-430	
10	2	ApT-10 / ApT-11	TGI-430	
11	3	ApT-1 / ApT-3 / ApT-6	TGI-320	
12	5	ApT-1 / ApT-3 / ApT-6	TGI-320	
		ApT-10 / ApT-11	TGI-430	
13	5	ApT-1 / ApT-3 / ApT-6	TGI-320	HAI-Inlet on ApT-4;
		ApT-10 / ApT-11	TGI-430	Belly Pod;Ventral Fin
14	5	ApT-3 / ApT-6	TGI-320	
		ApT-9 / ApT-10 / ApT-11	TGI-420	
15	5	ApT-3 / ApT-6 / ApT-9	TGI-320	LIF-OH Inlet on FWD VPT / FWD VPB;
		ApT-10 / ApT-11	TGI-430	DUALER Inlet on ApT-4
16	2	ApT-3 / ApT-1	TGI-320	CVI on FWD VPT; HAI on ApT-4; Drop Sondes Dispenser below RH Engine
17	4	ApT-3 / ApT-1 / ApT-6	TGI-320	CVI on FWD VPT; HAI on ApT-4; Drop
		ApT-10	TGI-430	Sondes Dispenser below RH Engine
18	4	ApT-3 / ApT-1 / ApT-6	TGI-320	CVI on FWD VPT; HAI on ApT-4; HASI on ApT-12; Drop Sondes Dispenser below RH Engine; 6 PMS Underwing External Stores
		ApT-10	TGI-430	

Figure 15: Build-up procedure (for steps 13; 15; 18 see figures 17 to 20)

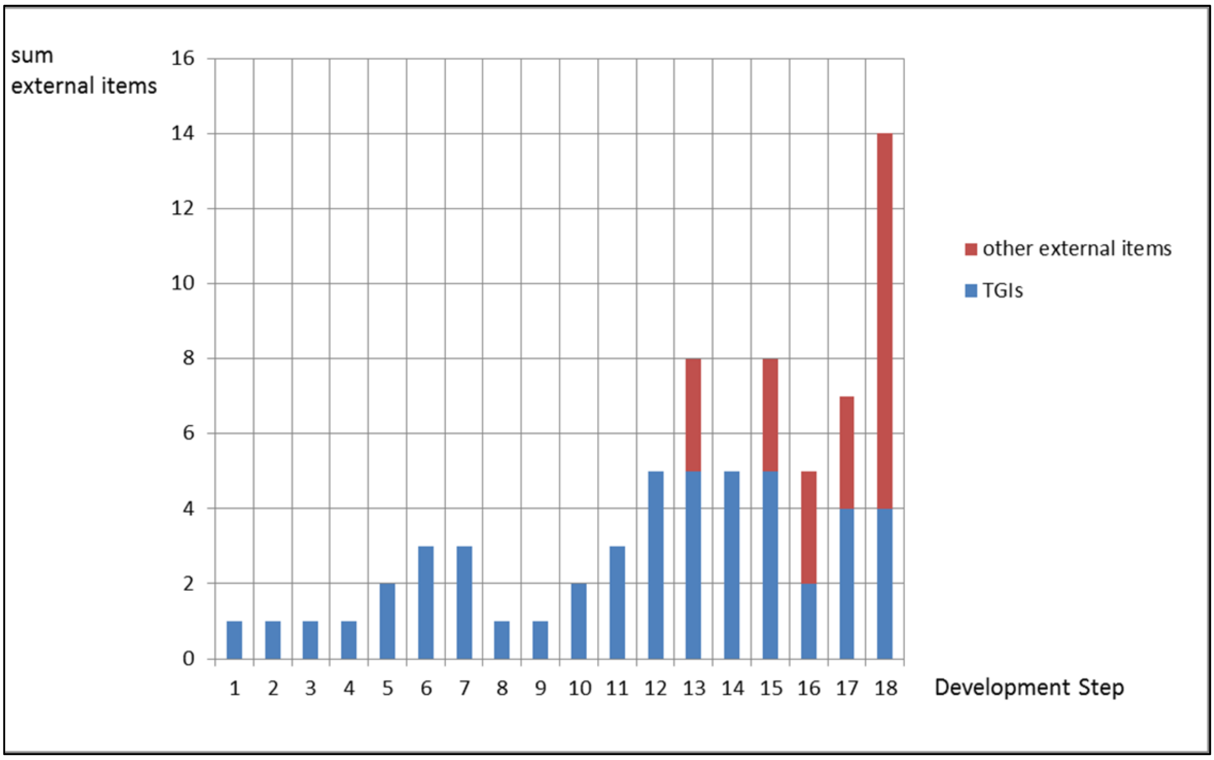

Figure 16: increasing complexity

Figure 17: Step 15

Figure 18: Step 15

Figure 19: Step 13

Figure 20: Step 18

Later on in the program and with growing experience of the TGI equipped aircraft's behaviour (Figure 16), the federal aviation office (the German Luftfahrtbundesamt) accepted a blend of the development phase and the certification phase.

2.3 Certification Phase

The certification phase answered all applicable airworthiness requirements of JAR25 Change 15's SUBPART B – FLIGHT. Later in the program the certification phase was blended together with the development phase and its Envelope Expansion Procedure which allowed a quicker certification of a set of the requested paragraphs by means of simple YES / NO answers to questions derived from the paragraphs. The set consisted of requirements of the chapters CONTROLLABILITY AND MANOEUVRABILITY; TRIM; STABILITY; MISCELLANEOUS FLIGHT REQUIREMENTS.
Eventually it was achieved to reduce the full flight test program's flights for a new TGI setup into two test flights: one for flying qualities with an aft CG and one for performance with a forward CG, answering all applicable paragraphs.
The second flight covers the applicable paragraphs of PERFORMANCE, including an accepted alternative testing method for JAR25.111 through 125 by means of level accelerations and decelerations.

The current test phases are completed with the issuance of a supplemental type certificate since April 2014.

3 VIBRATION MONITORING EQUIPMENT

DLR's G550 HALO being an atmospheric research aircraft is equipped with a highly precise basic atmospheric data sensor and acquisition system. Even though never a designated flight test data acquisition system, it provides a set of three usable analogue data ports that allow the use of piezoelectric equipment, such as accelerometers.
As time slots for testing were limited and scattered throughout the regular operation of the aircraft, an individual and full-blown flight test instrumentation system for the TGIs was no option. Therefore, existing hardware had to be used, such as the basic atmospheric data sensor and acquisition system and existing accelerometers of a size too big to be easily mounted inside the TGI.
For the flight tests, accelerometers (type: ASC 5521-010; range: 10g @ 1 kHz) were stuck to the base of the to-be monitored TGIs or their derivatives (Figure 21), such as the DUALER. A second accelerometer (type: ASC 5521-050; range: 50g @ 1 kHz) was mounted to the top of the TGI (and later removed) to calibrate the one accelerometer mounted to the base plate. Impulse strokes to the top of the TGI revealed the critical eigenfrequencies as well as the introduced acceleration of the top of the TGI (Figure 22). The accelerometer at the top measured the actual acceleration of the top. Impulse strokes introduced by the fist delivered superior results to those introduced by a hammer with PTFE tips. The accelerometer on the TGIs base showed a vibrational spectrum that was correlated to the input on the top. With an assumed linear proportion, the accepted g-limit of 20g for the lowest eigenfrequency (1st bending mode) in a range from 60Hz to 130Hz at the TGI's top [29] was defined in a Vrms value presented by the basic measurement system and displayed on a quick look laptop. The displayed value was in the y-direction of the accelerometer. Simple screen shots of the display / the displays at critical test points delivered the needed database for continuing flight testing and certification, where necessary (Figure 23). For every installation or re-installation of the base-plate mounted accelerometer a new calibration had to be conducted.

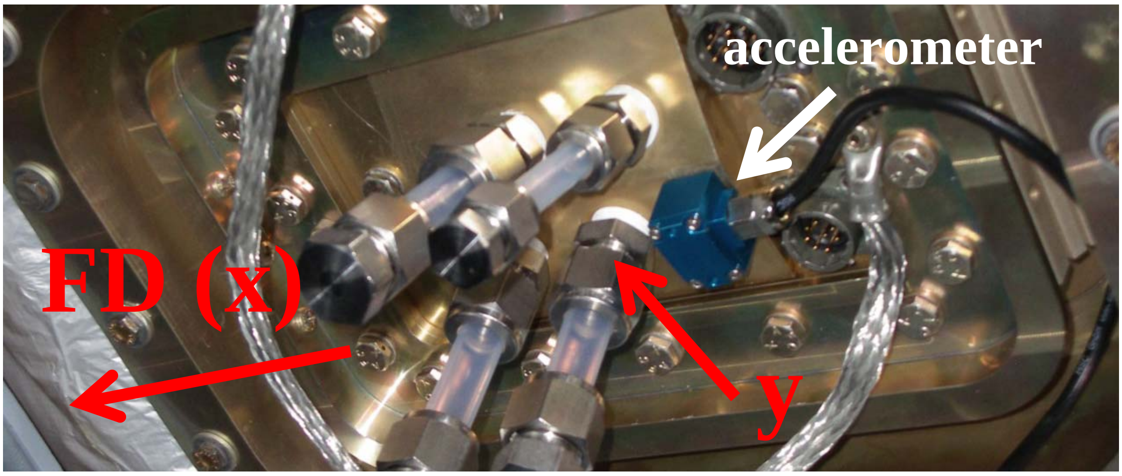

Figure 21: base-plate mounted accelerometer

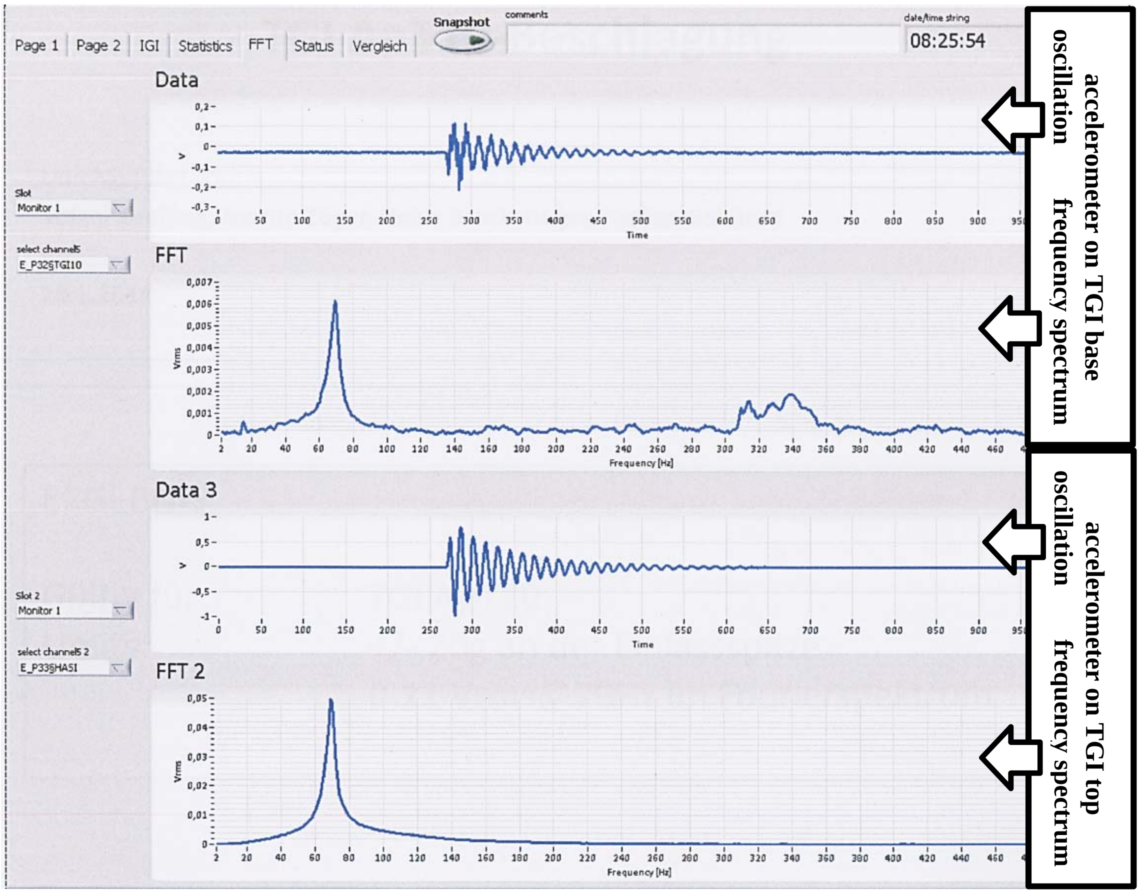

Figure 22: TGI accelerometer ground calibration, fist-stricken

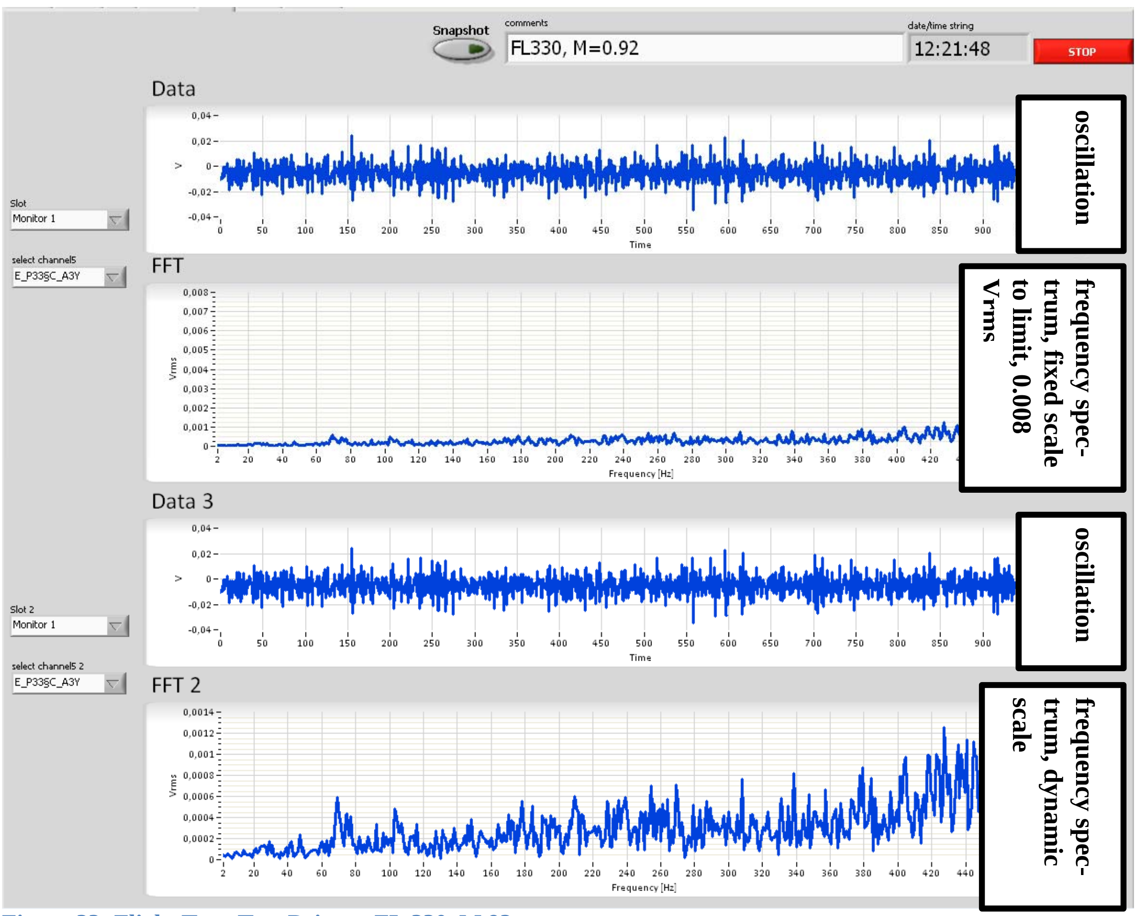

Figure 23: Flight Test, Test Point at FL 330, M.92

4 LESSONS LEARNT – FLIGHT TEST TEAM MANAGEMENT

4.1 Personnel Management

During the Test campaign the setup of the test team had changed various times, at one time in the "experimental phase" with thoroughly briefed, but with the subject completely unfamiliar test engineers to monitor the vibration levels. This led to a cancelled test flight, probably due to misinterpretation of the vibration readings if compared to later readings. Other setups that showed similar readings were tested successfully.

For test campaigns that start to show a similar complexity, it is suggested that the test team setup should include a better "backup personnel management" to avoid similar future situations.

4.2 Quality Management

Working on this paper showed a set of challenges to recapitulate the testing history. In one case the exact reason for repeated testing was not retrievable. The change made to the system, which led to the pilot report's suggestion to switch back to a former setup, could not be found in the available documentation. The reports showed great variations in terms of quality and detail, depending on the respective author.

It is suggested for each test flight report, even the pilot's flight test report, to briefly document the changes made to the system under test that initially led to conducting the specific flight test. A simple reference to the test plan is not sufficient. It is suggested additionally to re-define the minimum standards of what the (pilot's) test report should consist of.

5 ABBREVIATIONS

A/C	- Aircraft
ApB	- Aperture Plate Bottom
ApT	- Aperture Plate Top
BL	- Butt(ock) Line
CFD	- Computational Fluid Dynamics
CVI	- Counterflow Virtual Impactor Inlet
DLR	- Deutsches Zentrum fuer Luft- und Raumfahrt
DN	- Down
DUALER	- Dual Channel Airborne Peroxy Radical Chemical Amplifier
EASA	- European Aviation Safety Agency
EEP	- Envelope Expansion Procedure
FFT	- Fast Fourier Transformation
ft	- feet
GND	- Ground
GVFS	- Gulfstream V Frame Station
HAI	- Hygrometer for Atmospheric Investigation
HALO	- High Altitude and Long Research Aircraft
HASI	- HALO Standard Aerosol Inlet
JAR	- Joint Aviation Regulations
KCAS	- Knots Calibrated Airspeed
LBA	- Luftfahrtbundesamt
LBL	- Left Buttock Line
LIF-OH	- Laser Induced Fluorescence - Hydroxyl
M_{DF}	- Mach Number Dive
NCAR	- National Center for Atmospheric Research
PA	- Pressure Altitude
PMS	- Particle Measurement Sonde
PTFE	- Polytetrafluoroethylene
RBL	- Right Buttock Line
STC	- Supplemental Type Certificate
TGI	- Trace Gas Inlet
TLF	- Thrust for Level Flight
TOGA	- Take Off Go Around
TRA	- Traffic Restricted Area
USA	- United States of America
VPB	- View Port Bottom
VPT	- View Port Top
V_{DF}	- Dive Speed
Vrms	- Volts root mean square
V_{SR}	- Reference Stall Speed

6 ACKNOWLEDGEMENTS

Dr.-Ing. Martin Hepperle; Dipl.-Ing. Steffen Gemsa; Dipl.-Ing. Oliver Brieger; Dipl.-Ing. Katrin Witte; Dipl.-Ing. Michael Grossrubatscher; Dipl.-Ing. Kevin Raynor

7 REFERENCES

[1] M. Hierle, S. Gemsa "STALL TESTING ON A TRANSPORT CATEGORY AIRPLANE" 24th SFTE-EC Symposium, 11-13 June 2013, Braunschweig, Germany.
[2] European Aviation Safety Agency "EASA TYPE-CERTIFICATE DATA SHEET

EASA.IM.A.070 for GULFSTREAM GII, GIII, GIV & GV Issue 6”
[3] http://www.halo.dlr.de/aircraft/schemes/
[4] G550-56313-10-041-02_B_TGI_Flugbericht#F02
[5] G550-56313-09-073-080_TGI_FortfuehrungFlugerprobung
[6] G550-56313-10-041-04_A_TGI_Flugbericht#F04
[7] G550-56313-11-028 TGI-430&TGI-320 Development Flight Test Program
[8] G550-56313-11-031.01_A_StandardLuftEinlassTGI_#208
[9] G550-56301-11-031.02_A_Flugbericht Standard Lufteinlass TGI_#218
[10] G550-56301-11-031.03_A_Flugbericht Standard Lufteinlass TGI_#219
[11] G550-56301-11-031.04_A_Flugbericht Standard Lufteinlass TGI_#220
[12] G550-56301-11-031.05_A_Flugbericht Standard Lufteinlass TGI_#221
[13] G550-56301-11-031.06_A_Flugbericht Standard Lufteinlass TGI_#222
[14] G550-56301-11-031.07_A_Flugbericht Standard Lufteinlass TGI_#223
[15] G550-56301-11-031.08_A_Flugbericht Standard Lufteinlass TGI_#224
[16] G550-56301-11-031.09_A_Flugbericht Standard Lufteinlass TGI_#225
[17] G550-56301-11-031.10_A_Flugbericht Standard Lufteinlass TGI_#226
[18] G550-56301-11-031.11_A_Flugbericht Standard Lufteinlass TGI_#227
[19] G550-56301-11-031.12_A_Flugbericht Standard Lufteinlass TGI_#228
[20] G550-56301-11-031.12_A_Flugbericht Standard Lufteinlass TGI_#230
[21] G550-56301-11-031.14_A_Flugbericht Standard Lufteinlass TGI_#231
[22] Dr.-Ing. Martin Hepperle, E-Mail to Sebastian Burwitz; Subject:„ AW: TGI Status Quo Präsentation 16-03-2012“; 16.04.2014 – Image courtesy Martin Hepperle, DLR-AS, Braunschweig,
[23] G550-56313-12-033-1_B_TGI_Developmental Flight Test Report_SplitterPlate+Zigzag
[24] Van Dyke, M: *'An Album of Fluid Motion'*, The Paraboloic Press, Stanford CA, 1982
[25] G550-56313-09-073-022_A_TGI-FlugerprobungSplitterPlate
[26] G550-56313-12-029.1_A_TGI Splitter Plate PFR_#249
[27] G550-56313-12-029.2_A_TGI Splitter Plate PFR_#250
[28] G550-56313-13-059_C_Flight Test Program
[29] G550-56313-11-073.120_A_Schwingungsverhalten des TGI mit Einspannmodifikation