THE «FLIGHT TESTING» GRADUATE COURSE AT POLITECNICO DI MILANO

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Abstract: This paper describes the current status of the "Flight Testing" graduate course held at the Politecnico di Milano as an elective subject in its Aeronautical Engineering MSc curriculum. The course, delivered each year, has reached its 10th anniversary in 2015. Nearly 120 students passed the course to date, most of them upon submission and presentation of a flight test report concerning a real flight test mission carried out by the student in person. In fact, the unique characteristic of this course is the provision of a complete experience in which each student is requested to design, perform and report on a real flight test of a manned aircraft, acting as a Flight Test Engineer under all respects. The conditions of the flight test experience and two flight test campaigns are described, reporting on the latest updates in the FTI system, which now features a fully functional telemetry capability.

1 LIST OF SIMBOLS

A/C	Aircraft
AOA	Angle of attack
AOS	Angle of sideslip
CAN	Controller Area Network
CDIO	Conceiving – Designing – Implementing – Operating
COTS	Commercial off-the-shelf
CTO	Chief technical officer
CVE	Compliance verification engineer
DSTA-PoliMI	Department of Aerospace Science and Technology, Politecnico di Milano
GPS	Global Positioning System
GS	Ground station
HDO	Head of design organization
FT	Flight testing
FTE	Flight test engineer
FTI	Flight test instrumentation
FTR	Flight Test Report
MEMS	Micro Electro-Mechanical Systems
MTOW	Maximum take-off weight
TPD	Test Planning Document
UDP	User Datagram Protocol
ULM	Ultralight machine

2 INTRODUCTION

2.1 Motivation

Flight Testing (FT), *i.e.* the process of acquiring data related to a flying machine in actual flight, is, by its very nature, a strongly multi-disciplinary activity as the many Aeronautical Engineering disciplines collaborating to the realization of a flying machine (aerodynamics, flight mechanics, aircraft structures, propulsion, mechanical systems, electrical systems, hydraulic systems, control systems, human-machine interface and ergonomics, etc.) are all involved in the trial and verification of its behavior. FT theoretical and experimental methodologies are grounded on these disciplines, together with fundamental input from the theory and practice of measurement in engineering. Therefore, in addition to the interest in FT as a discipline in itself, a dedicated course placed at the end of the MSc academic path represents an ideal ground to integrate, synthesize and verify a vast multidisciplinary knowledge base acquired by the graduate student in the previous courses, leading to a final overall consideration of the complete aircraft as a system of strongly interacting systems. In addition, the student can learn how to operate in compliance with applicable regulations and procedures in a typical aeronautical real-life environment and can get a taste of a strongly job-related, specialized activity which involves a selected group of professionals in industrial applications.

Notwithstanding, FT as an engineering discipline in itself is rarely considered as "the" subject of a dedicated graduate course, and only a few universities include a FT-dedicated course within their Aeronautical Engineering curricula. More often, FT theory is included in bits and pieces within more classical academic courses (*e.g.* flight mechanics, flight dynamics and control, experimental techniques for aerospace, etc.).

Based on the previous considerations, in 2005 the Politecnico di Milano started to deliver a dedicated FT course to its graduate students, especially those majoring in "Flight mechanics and flight systems" (one of the 5 main specializations currently suggested to MSc students, along with "Aerodynamics", "Aerostructures", "Propulsion" and "Rotary-wing aircraft"). Up to 2012, the course was entrusted to top-level FT experts from the industry, supported by DSTA-PoliMi staff. Paolo Chimetto (formerly M346 FT Manager, currently M-346 Chief Engineer/CTO/HDO at AleniaAermacchi) was the teacher in charge, assisted by Giovanni Bonaita (ret., formerly FT Manager at SIAI Marchetti and Aermacchi, and subsequently CVE at AgustaWestland). The authors were also involved in laboratory activities, with the first author taking the full charge of the course from 2012 onwards. The present paper updates the account provided in Ref. 1.

2.2 Background activities

FT-related activities at Department of Aerospace Science and Technology (DSTA-PoliMI) included early experiences in the design, construction and modification of ultralight manned aircraft carried out in the 1990's. Also, activities on fixed- and rotary-wing UAVs were pursued and are currently undergoing, especially in the field of autonomous navigation and control. However, a major step in view of the present discussion was the acquisition of a Tecnam P92 Echo ULM (ultralight machine) in 1998 (Figure 1). This is a fixed-wing, three axis control aircraft that has been directly operated by DSTA-PoliMI for about ten years, as a support for both educational activities – such as "first-flight" or familiarization flight missions of 1st-year students – and research pursuits – such as the in-house development of low-cost flight instruments and flight test instrumentation.

Figure 1: The DSTA-POliMI P-92 Echo ultralight airplane.

Up to 2008, the P92 was used to perform the flight test missions of the “Flight testing” course. Indeed, such an airplane is fully representative of typical fixed-wing, heavier general aviation aircraft such as those falling in the CS-VLA or FAR/CS-23 type certification, save for the costs of operation and maintenance, which are substantially lower, allowing to establish a sustainable, recurring activity over the years.

Concurrently, DSTA-PoliMI is engaged in the ongoing development of an ULM-dedicated flight test instrumentation (FTI) system: the “Mnemosine” integrated FTI suite. This was initially designed and implemented by the second author within his PhD project, started in 2005. The goal was to provide a safe, economic and reliable FTI system capable to be installed with minimal intrusiveness to ultralight and very light aircraft, in view of its application to a typical certification campaign. Therefore, FTI requirements included the ability to support all the main certification-related tasks, such as the determination of airfield performance, flight performance and flying qualities, the assessment of on-board system performance, the modelling and identification of the airplane aerodynamics and engine. As a result, the “Mnemosine” system, in its basic version, includes an air data module, an inertial measurement module, a GPS module, an engine module, a flight control position module, a flight control force module, plus a power supply module, a data logging module and a command a display module. These elements are federated in a highly flexible architecture that provides a dual 1 MBit/s Controller Area Network (CAN) based digital data bus as a common communication line. Timing information is also distributed across the whole system for inter-module synchronization purposes. The “Mnemosine” FTI system is described in detail in Refs. 2-4.

As from 2009, DSTA-PoliMI started a collaboration with Club Astra, a flying school operating the Mezzana Bigli airstrip (some 80 km South-West from the Politecnico di Milano premises) and Ing. Nando Groppo Srl, a reputed ULM manufacturer, in order to enhance the overall efficiency of the educational flight missions. As a result of this fruitful relationship, some activities have been performed in recent years in support of Ing. Nando Groppo Srl product development and qualification. The peak of this collaboration involves the certification of two models according to the German LTF-UL 2003 regulations. The first model, the “Trail” (formerly known as “Trial”), was successfully certified in 2011, building also on the educational flight missions performed in 2010. A detailed account of this groundbreaking activity is given in Ref. 5. The second is a newly developed model and the FT campaign is currently undergoing (Autumn 2015). In both cases, DSTA-PoliMI provided scientific and technological support, with the “Mnemosine” FTI suite as a fundamental ingredient, allowing accurate post-processing of reliable FT data.

3 COURSE CHARACTERISTICS

The “Flight Testing” graduate course is intended as a “capstone” course in the final year of the Aerospace Engineering MSc *cursus studiorum*, with the aim to provide fundamental concepts and skills on the FT process, its principles, techniques, organization and practical execution. To this end, the course is established with a ‘classical’ structure of lectures and exercises, complemented by a Conceiving – Designing – Implementing – Operating (CDIO) activity in which engineering fundamentals are stressed in the application to real-world systems and products, such as the aircraft and the FTI system. The classical part involves a program adhering to the typical outline of an introductory course offered in a professional FT school:

1. FT motivation, historical development, process schematics, classification, applicable regulations (with an emphasis on EASA CS-23 and CS-VLA);
2. Review of fundamental concepts from various aeronautical disciplines;
3. FT theory and methodologies (air data calibration, performance, stability and control, high AOA, loads, aeroelasticity, propulsion, systems, data reduction);
4. Examples of special tests (noise certification, icing, hot weather operations, weapons, flow visualization, vibrations, etc.);
5. FTI: parameter set definition, on-board and ground system architectures, data acquisition systems, data processing methods;
6. FT planning and execution: organization, requirements, test program, mission planning, data processing and analysis, reporting, compliance with regulations.

This typically involves 30 hours of theory lectures (including a few seminars delivered by experts from the industry) and 22 hours of explanations and exercises on FT techniques and practical methods.

The CDIO part consists in the provision of a real, complete flight test experience, complemented with all the necessary preparatory activities. In fact, each attending student is required to plan, individually perform and report on a complex flight test mission, acting as a flight test engineer (FTE) under all respects. Therefore, a full array of experimental laboratories are carried out, mainly in the second half of the course duration (4 months), including:

1. Inspection and familiarization with the FTI system on the DSTA-PoliMI integration and test rig;
2. Inspection and familiarization with the airfield, its facilities, ground operations, safety procedures;
3. Inspection and familiarization with the aircraft and the installed FTI system;
4. FTI transducer calibration for the flight controls and corresponding control surface deflection;
5. In some cases, FTI air data system calibration in one of the DSTA-PoliMi wind tunnels;
6. The required number of FT missions.

The FT missions are conceived and carried out by the students typically grouped in two-person teams, one flight mission for each student. Each mission comprises several test points related to three or four distinct test topics sorted out of the list detailed in Table I.

Table 1: FT mission themes.

Area	Topic
Air data calibration	Static error correction
Field performance	Take-off
	Landing
	Balked landing
Flight performance	Level flight stalls (TO, CR, LND)
	Power-on stalls (TO, CR, LND)
	Turning flight stalls (TO, CR, LND)
	Cruise performance, max airspeed in level flight
	Climb performance (TO, CR, LND)
	Glide performance (TO, CR, LND)
Flying qualities	Static stability and control (TO, CR, LND)
	Manoeuvring stability, roll performances
	Dynamic stability (TO, CR, LND)
On-board systems	Radio range

Note: The tested aircraft configurations are take-off (TO), landing (LND) and cruise (CR)

As apparent, the FT topics are representative of a wide variety of typical mission tasks within the normal aircraft flight envelope. Of course, safety considerations are of primary importance in the preliminary screening of the test points to be performed, and a test hazard assessment is requested as a part of the Test Planning Document (TPD) to be compiled by each team prior to the FT campaign. The TPD details test requirements and objectives, required aircraft configuration, required instrumentation, test conditions, proposed FT techniques and manoeuvres, pass/reject criteria, possible constraints and applicable norms and limitations.

Upon approval by the teacher of the TPD, the team produces appropriate flight cards, detailing the sequence of test points to be flown. These are subjected to a preliminary verification by the teaching staff and by the designated test pilot and possibly the aircraft manufacturer or operator, and amended in case of need. Furthermore, on the scheduled day, the team conducts a pre-flight briefing with the test pilot reviewing the proposed mission a last time.

Subsequently, the flight missions are performed with the students sitting in the cockpit with the pilot. In this peculiar task, they act as the FTE in charge, co-operating with the pilot in carrying out the test sequence, taking note of instrument readings as appropriate, operating the ‘Top’ marker switch that identifies each test point, verifying the correct execution of the planned manoeuvres, and directly checking the behaviour of the aircraft and its systems. Typically, each team member flies the same or a very similar mission. This provides the possibility to cross-check the results and mitigates the risk connected to partial data loss, incorrect flight techniques, changing meteorological conditions, and other possible inconveniences.

After the flight, acquired data are downloaded from the “Mnemosine” data storage unit and preliminarily visualized on a PC set-up at the airfield. A debriefing with the pilot is carried out in order to comment on the execution of each mission task, possible difficulties encountered, need to repeat specific test points, and the like. After the completion of the mission, stored data are post-processed by the students. Acquired signals are first converted to engineering quantities, then these quantities are validated, filtered and sampled as appropriate, providing the test flight results. In the subsequent analysis, these results are related to the test objectives, critically discussed and evaluated, to be finally presented in a Flight Test Report (FTR). This, together with the TPD, is a mandatory requirement for evaluation, and must contain also the considerations related to compliance with the requirements, FTE comments, conclusions and recommendations.

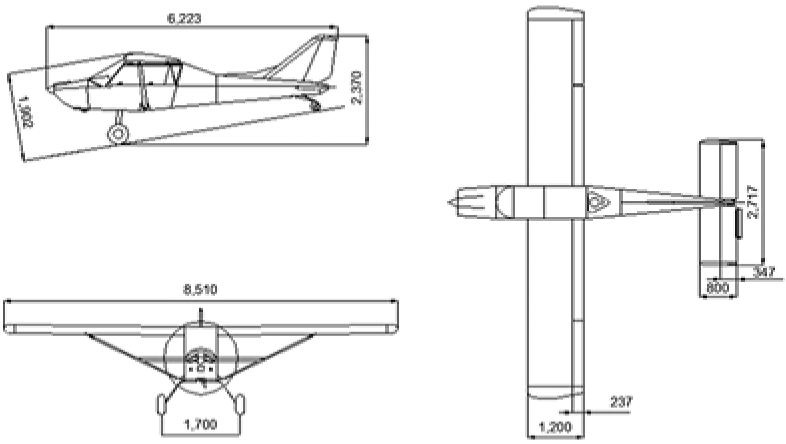

Figure 2: The NG "Trial" ultralight airplane.

4 RECENT FLIGHT TEST CAMPAIGNS

The 2014 and 2015 flight test campaigns can be regarded as typical examples of the "Flight Testing" course activities. In both cases, the "Mnemosine" FTI system allowed the acquisition of over 30 parameters including air data (static pressure, dynamic pressure, outside air temperature, angle of attack, angle of sideslip), inertial kinematic quantities (body-frame acceleration components, attitude angles, angular velocity components), GPS kinematic quantities (earth-centered, earth-fixed co-ordinates and groundspeed components), flight control positions (stick and pedal position) and piloting forces (stick and pedal forces), engine data (engine RPM). An event counter signal was included and to identify single trim points and maneuver durations. A display unit was also provided to allow the crew monitor a few parameters on-the-fly, while performing the test.

In May 2014, the "Mnemosine" FTI system was installed on board the Ing. Nando Groppo Srl "Trail" model (Figure 2), including an air data boom provided with AOA and AOS vanes (Figure 3). The "Trail" is a rugged taildragger, tandem-seat, high wing, all-metal airplane conceived for training and leisure flight with a 600 kg_p design MTOW, powered by a 100 HP four-stroke aspirated engine.

Figure 3: The FTI pitot boom installed below the “Trial” right wing.

The 2014 flight test campaign involved a total of 15 flight test missions, carried out during 4 afternoons. No repetitions were necessary. Each mission had a duration (from engine start to engine stop) between 41 and 60 minutes, with an average of 48.5 minutes. Two aircraft versions have been tested, one with a clean wing, and another with a wing fitted with vortex generators (VGs) close to the leading edge, on the upper surface. Half of the teams were assigned to a number of topics on the clean airplane, while the other half performed the same studies on the aircraft fitted with VGs. The specific topics, in addition to take-off and landing performance, are listed below for each team:

- Team 1 (2 missions): air data calibration, roll performance (26 test points total each mission) – clean A/C;
- Team 2 (2 missions): idle stalls, speed stability (14 test points total each mission) – clean A/C;
- Team 3 (2 missions): sawtooth climbs and glides, phugoid (11 test points total each mission) – clean A/C;
- Team 4 (2 missions): air data calibration, roll performance (26 test points total each mission) – A/C with VGs;
- Team 5 (2 missions): idle stalls, speed stability (8 test points total each mission) – A/C with VGs;
- Team 6 (2 missions): sawtooth climbs and glides, phugoid (12 test points total each mission) – A/C with VGs;
- Team 7 (3 missions): speed power, maneuvering stability (21 test points each mission) – 1 flight on clean A/C, 2 on A/C with VGs.

The students presented their FTRs in the months following the end of the course in June. Their analysis revealed that negligible variations occur between the two wing configurations with respect to stability and control items such as maneuvering stability (stick force per ‘g’), phugoid behavior and roll performance. Also landing performance did not seem to be affected. On the other hand, in reference to the same flight conditions, the VGs reduced take-off distance by 7% and stall speed in cruise configuration by 12%. It has to be noted that in all cases, the stall event was attained due to limitations in the longitudinal control authority – a case often encountered in ULMs. As a drawback, significant reductions in maximum rate of climb (estimated as 15-30%) and maximum angle of climb (15-20%) were observed, with corresponding slight reductions of the airspeed for fastest climb.

In May 2015, a new version of the "Mnemosine" FTI system (Mk V) was installed on board the Ing. Nando Groppo Srl "Folded" model. This is an earlier product, very similar to the "Trial", but characterized by side-by-side seats and by a tricycle landing gear.

In this occasion, some important new additions to the flight test instrumentation were integrated and tested. First, a bi-directional telemetry channel based on COTS hardware has been developed and implemented. The link to the A/C is provided by an 802.11n 2.4 GHz system, featuring a couple of high gain, directional antennas on the ground actively steered to maintain the correct tracking (Figure 4). The antenna tracking unit is connected to the Ground Station (GS) through an additional 802.11n link on the 5 GHz band, allowing antenna positioning far away from the GS. Flight data were sent from the A/C as a stream of small (57 bytes payload) UDP packets. The possibility of sending additional streams of audio and video is present, and will be exploited in the future versions of the system.

The ground infrastructure is completed by a weather station that acquires air temperature, pressure, relative humidity information, as well as and wind intensity and direction, and conveys it to the GS via the cited 802.11n link on the 5 GHz band.

Figure 4: The NG "Folder" at touchdown, closely followed by the telemetry antennae (on the left).

The 2015 flight test campaign involved a total of 11 flight test missions, carried out during an a afternoon and a full day. One repetition was necessary due to a loss of fata during the first flight. Each mission had a duration between 31 and 56 minutes, with an average of 46.8 minutes. In this case, the A/C was tested in a single (VG-fitted) wing configuration. The specific topics, in addition to take-off and landing performance, are listed below for each team:

- Team 1 (2 missions): speed power, Dutch roll (10 test points total each mission);
- Team 2 (2 missions): idle stalls, maneuvering stability (14 test points total each mission);
- Team 3 (2 missions): idle stalls, speed stability (10 test points total each mission) – clean A/C;
- Team 4 (3 missions): sawtooth climbs and glides, phugoid, roll performance (14 test points total each mission);
- Team 5 (1 mission): air data calibration (8 test points).

Currently, the students are still working to prepare their FTRs.

5 OTHER RELATED ACTIVITIES

As anticipated, the DSTA-PoliMI team involved in the “Flight Testing” course is currently working on the planning, execution and post-flight analysis related to the LTF-UL certification campaign for the new ULM model designed at Ing. Nando Groppo Srl. In this circumstance, the newly-developed telemetry system and GS are being used together with the “Mnemosine” FTI system in order to collect the necessary data. The GS interface provides the real-time cockpit-like view of on board flight instruments (Figure 5), as well as the typical paper strip-like visualization of the time histories of all sensed parameters. Apart from its general usefulness in monitoring the test point quality in real-time from the ground, it is expected that the telemetry capability will be especially advantageous in all the test missions flown at minimum weight, and therefore without the FTE on board. In those cases, the FTE will be operating the GS while keeping constant radio communication with the pilot, in order to support the test point achievement.

Figure 5: The Ground Station main monitor, showing the airplane’s flight instrument readings supplied by the telemetry link.

Also connected to the “Flight Testing” course, two currently ongoing activities concern the usage of small unmanned fixed-wing aircraft. The first (Ref. 6) pursues the development of automated FT procedures for UAVs, by implementing dedicated operational modes on the autopilot of an existing model, the “Cularis”. This is an electric radio-controlled motorglider with folding propeller with a 2.6 m wingspan and weighing 2.1 kg_p. The model is provided with an open-source autopilot, Arduino-compatible, complemented with a full suite composed by an air data sensor, a GPS receiver and an integrated MEMS-based 3-axis gyro and accelerometer. The “Cularis” has been fitted with two symmetrical air data booms on each wing, one carrying the pitot-static system, and the other dedicated to the AOA and AOS vanes (Figure 6). In this way, it has been possible to perform several test missions using autonomous FT modes for trimmed flight, steady full-power climbing and power-off gliding flight, and stalls at various deceleration levels. This has shown the feasibility of performing standard flight tests, according to the accepted practices employed for manned aircraft, using a very low-cost UAV platform, by-passing the difficulties related to remote piloting, which cannot guarantee adequate precision and repeatability in such tasks.

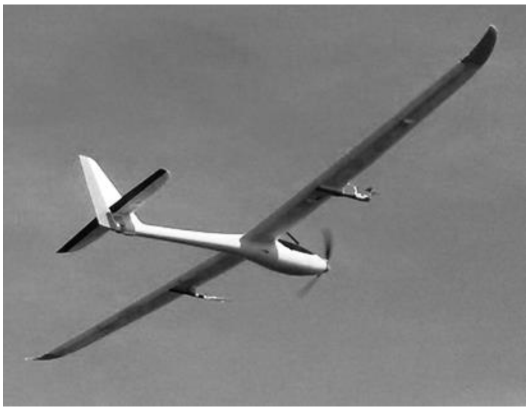

Figure 6: The "Cularis" symmetrically fitted with two air data booms: AOA and AOS vanes (right) and pitot-static (left).

The second activity involves the in-house development of another very low-cost UAV system, the "Chippy" program (Refs. 7, 8). This consists in a small flying-wing aircraft with 640 g_p MTOW, 1.2 m wingspan, featuring a multi-sensor suite (GPS, inertial data, magnetometer, air data, propulsion data, system state), an on-board secure digital memory card-based data recorder, and a 802.15.4, 2.4 GHz-based telemetry link to the ground station. In this case also, automated FT procedures are pursued through an electronic flight test system, which allows to define the sequence of test points at mission planning time, load them on the electronic flight card subsystem and have the on board test point director, triggered by the pilot on ground, autonomously execute them.

6 CONCLUDING REMARKS

The recent experiences matured in the delivery of the "Flight testing" course confirm that this kind of activity is an ideal ground to check, consolidate and improve the student's understanding of the aircraft, its systems, its operational use, in a very active and creative way. The responsibility of planning and performing a complex task such as a flight test mission is a precious addition to the cultural baggage gained in the MSc *cursus studiorum*. As a result, the students gather the impression that the course is one of the most fruitful activities in their last year of studies.

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