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Reliable and Cost-Effective Flight Testing of Ultralight Aircraft

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This paper reports upon an integrated approach to the flight-testing campaign of a new ultralight machine airplane model toward its certification according to the German airworthiness requirements. Flight trials have been completed, resulting in full compliance with the above regulations, and the certification process has been successfully accomplished. This result ensues from a cooperative effort of the team formed by the aircraft manufacturer and a research group of the Department of Aerospace Engineering at the Politecnico di Milano, including both permanent and external staff, together with a varying number of graduate students. The academic contribution consists of the support to flight-test mission planning, flight-test operations, data processing and analysis, as well as in the supply and management of the Mnemosine flight-test instrumentation system. This project highlights the availability of both the necessary expertise and an economic, dependable, simple, and complete flight-test instrumentation system dedicated to light aircraft, opening full access of small size manufacturers to cost-effective, reliable, systematic flight-testing procedures, in view of enhanced flight safety and overall quality of ultralight machine operations.

Introduction

HISTORICALLY, the Department of Aerospace Engineering of the Politecnico di Milano (hereafter, referred to as DIA-PoliMi) has often been involved in flight testing, albeit on a limited scale. Examples include the design and construction/modification/operation of both fixed- and rotary-wing unmanned aerial vehicles (UAVs) and ultralight machines (ULMs), with the latter term identifying manned airplanes of a size smaller than that allowed by the European very light airplane (VLA) or the U.S. light sport aircraft (LSA) categories. However, in recent years, DIA-PoliMi has developed a specific line of education and applied research focused on flight testing.

In 1998, DIA-PoliMi went as far as buying a high-end ULM (a Tecnam P92 Echo), directly operating it to support flight-related activities. Initially, the airplane was used in flight familiarization experiences for undergraduate students. Gradually, in the subsequent years, it has grown to be a flying laboratory for the study and development of flight instrumentation.

A fundamental step toward building up a solid expertise in flight testing has been accomplished with the design, development, and implementation of the flight-test instrumentation (FTI) system Mnemosine. This started as the core of a Ph.D. project in 2005 and has resulted in a proprietary integrated FTI suite tailored on light aircraft, such as ULMs and general aviation fixed- and rotary-wing vehicles, and it is capable of supporting a wide range of flight-testing activities ([1,2]). The system has reached a considerable degree of maturity, albeit undergoing continuous improvements and expansions, following both technological progress and application needs ([3,4]).

A second important element is the graduate course of Sperimentazione in Volo (flight testing). This course, incepted in 2004, has been regularly held in the second semester of the final year of the M.S. degree program in aeronautical engineering. Teaching duties have been entrusted to top experts from world-class aeronautical organizations, such as Alenia Aermacchi and AgustaWestland, working in cooperation with DIA-PoliMi permanent staff. The program closely adheres to the typical outline of an introductory course offered in a professional flight-testing school. This course is fairly unique, given that it involves a real flight-testing experience on a real airplane, in addition to theory lessons and application laboratory hours. In fact, each attending student is required to plan, individually perform, and report on a flight-test mission, acting as a FTE (flight-test engineer) under all respects. The interested reader is directed to [5–7] for details.

A further initiative is the collaboration of DIA-PoliMi with the Club Astra flying school and Ing. Nando Groppo s.r.l., a leading Italian ULM manufacturer. This effort, started in 2008, is directed to support didactic activities, such as the flight missions of the flight-testing course, as well as the manufacturer's flight-testing needs. In particular, Ing. Nando Groppo s.r.l. was seeking support in the process of type certification of its recent Trial model, a new three-axis control ULM, in an effort to expand its market on a European scale.

Motivation

Given the nearly absent regulations for ULMs in Italy, as well as in many other countries, manufacturers have typically not been drawn toward undertaking a well-established rigorous flight-testing program with all the related investments, let alone a complete certification procedure according to severe requirements, such as those featured by the LTF-UL (Airworthiness Requirements for Aerodynamically Controlled Ultralight Aircraft) standards addressed in the present paper. As a result, in many cases, consistent flight testing is plainly avoided, with easily deducible consequences on the safety of ULM operations at large.

This state of affairs could be deeply improved by building upon the results of the activity described in this paper. This involves a Trial machine that has been fitted with DIA-PoliMi's Mnemosine FTI system, undergoing an articulated flight campaign ranging over the whole LTF-UL items that require demonstration in flight as a necessary means of compliance. Results from this campaign amount to a globally successful experience, where flight-testing procedures, instrumentation, and analysis methods have proven to be safe, practical, effective, and fully sustainable. This project has been presented in [8] and is documented in greater detail in the present paper.

DIA-PoliMi's Mnemosine FTI system

As anticipated, in order to start off with both didactic and research flight-testing projects on DIA-PoliMi's Tecnam P92 Echo, the aircraft needed to be equipped with an appropriate FTI system. Given the limitations of a PC-based general-purpose data-acquisition

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system and willing to acquire and maintain detailed knowledge, effective control, and high flexibility of the data-acquisition process, a specific activity aimed to design, develop, and test a ULM-tailored FTI system has been launched as the main topic of a Ph.D. project, eventually yielding the Mnemosine system.

Mnemosine requirements have been deeply influenced by the research-oriented nature of the project. In fact, apart from the unavoidable low-budget constraints, the highly dynamic nature of the project called for a system capable of being upgraded or maintained in one or more components without affecting the operational capability of the remaining parts. In addition, it was clear that it was necessary to provide a huge growth potential, accounting for the predictable expansion of the system as new inputs from research activities would arise.

System Architecture

Mnemosine is characterized by a federated architecture in which the system is split up in a number of autonomous nodes, as shown in Fig. 1. Every single node can operate independently from each other, and each is specialized for a specific task; it is endowed with processing power, memory, power supply, and all the signal conditioning and interface resources required to manage its corresponding sensor or device. All data generated by the modules are shared over a common wired communication line: a dual 1 Mbit/s controller area network (CAN)-based digital data bus. Currently, the system uses two independent data buses: the D-bus for acquired data communication between nodes and the T-bus exclusively dedicated to timing information distribution for internode synchronization purposes.

Among the advantages of this architecture is the ability to distribute the units throughout the aircraft, which permits every module to be placed as closely as possible to the corresponding sensor, avoiding the need to lay down long noise-sensible analog signal lines. Information is immediately converted to a digital format, processed, and transmitted over a robust medium. This leads to a globally mitigated impact upon the aircraft, facilitating internal space optimization. Compared with centralized architectural solutions characterized by a simpler design, software partitioning and fault confinement are inherently guaranteed and a higher degree of system modularity and flexibility is achieved, with nodes specialized for each particular task and customized upon corresponding sensors.

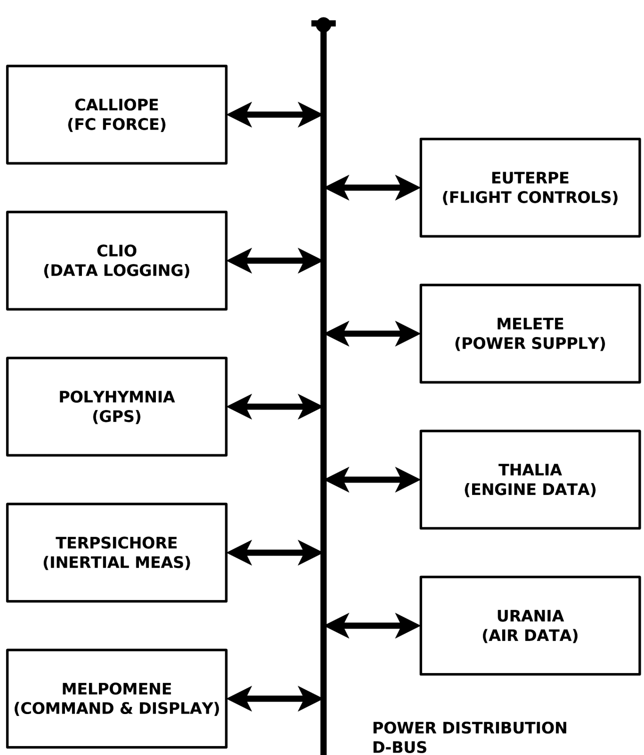

Fig. 1 Block diagram of the Mnemosine FTI system showing its federated architecture.

Table 1 FTI node functions

Node name	Node task
Eutherpe	Flight control position acquisition
Klios	Data logging
Melete	System power management and distribution
Polimnia	GPS data acquisition and system time generation and distribution
Talia	Engine data acquisition
Terpsicore	Inertial measurement acquisition
Urania	Air-data acquisition
Melpomene	Command and display unit
Calliope	Flight control force acquisition

The system name comes from ancient Greek mythology. Having chosen a federated architecture, the idea arose to assign the name of one of the *Muses* (the nine sister goddesses presiding over song, poetry, arts, and sciences) to each node; with *Mnemosine* being the goddess of memory and the mother of the Muses, it seemed only natural to assign her name to the whole system.

In the configuration used for the present activity, Mnemosine was composed of the nodes described in Table 1, each acquiring the indicated subset of parameters and/or managing the indicated operation.

Data Acquisition

All parameters and data undergo a twofold process before they finally become available to the user. The basic philosophy inspiring data flow design is to perform onboard, in real time and at node level, only the operations strictly necessary for the acquisition of a parameter from a sensor, its conditioning, and filtering, down to transformation into engineering units, time-stamping (a crucial feature, to be addressed hereafter), and storage on nonvolatile memory (Fig. 2).

Table 2 lists the full array of acquired parameters, together with the respective node and their acquisition rate with respect to the current system implementation.

The crucial need for reliable and accurate data time-referencing feature has inspired the development of CAFFE (CAN for flight-test

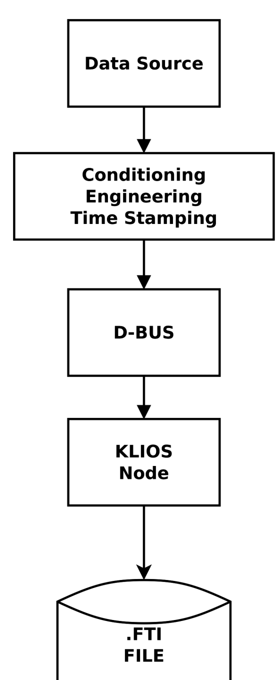

Fig. 2 Onboard real-time data flow schematics.

Table 2 FTI parameter list

ID	Parameter	Node	Rate
01	X acceleration	Terpsicore	60 Hz
02	Y acceleration	Terpsicore	60 Hz
03	Z acceleration	Terpsicore	60 Hz
04	Pitch angle	Terpsicore	60 Hz
05	Roll angle	Terpsicore	60 Hz
06	Yaw angle	Terpsicore	60 Hz
07	Pitch rate	Terpsicore	60 Hz
08	Roll rate	Terpsicore	60 Hz
09	Yaw rate	Terpsicore	60 Hz
10	Elevator control position	Eutherpe	10 Hz
11	Aileron control position	Eutherpe	10 Hz
12	Left pedal position	Eutherpe	10 Hz
13	Flap position	Eutherpe	10 Hz
14	Rudder force	Calliope	10 Hz
15	Aileron force	Calliope	10 Hz
16	GPS time of week	Polimnia	4 Hz
17	GPS week no.	Polimnia	4 Hz
18	GPS X position (ECEF)[a]	Polimnia	4 Hz
19	GPS Y position (ECEF)	Polimnia	4 Hz
20	GPS Z position (ECEF)	Polimnia	4 Hz
21	GPS X velocity (ECEF)	Polimnia	4 Hz
22	GPS Y velocity (ECEF)	Polimnia	4 Hz
23	GPS Z velocity (ECEF)	Polimnia	4 Hz
24	GPS fix quality	Polimnia	4 Hz
25	GPS tracked satellites	Polimnia	4 Hz
26	GPS dilution of precision	Polimnia	4 Hz
27	Propeller rpm	Talia	2 Hz
28	Total pressure	Urania	10 Hz
29	Static pressure	Urania	10 Hz
30	Angle of attack	Urania	10 Hz
31	Angle of sideslip	Urania	10 Hz
32	Event (top) counter	Melpomene	——

[a]GPS data are provided in the Earth-centered, Earth-fixed (ECEF) reference frame.

equipment), a variation of CANAerospace, which is a widely used protocol targeted to avionic systems. With respect to CANAerospace characteristics of robustness, efficiency, lightness, good performances, and large diffusion, CAFFE adds a built-in data time-stamping capability. This customization has been obtained with a different use of available bits in the CAN message extended-identification field, together with the use of two separate CAN buses. In fact, the T-bus supports the distribution of the timing information acquired by Polimnia, the Global Positioning System (GPS) unit. As a result, CAFFE allows network time synchronization (i.e., timing information is shared across nodes) and time tagging (i.e., precise time information is associated with each datum), with a resolution of 1 ms. Both of these characteristics are fundamental in view of flight-testing applications, where synchronization of time histories pertaining to a number of independent parameters is necessary to achieve reliable insight into the phenomena being investigated.

Data Analysis

After data acquisition, all subsequent operations (such as computation of derived parameters or information fusion from different sensors) are left to an offline postprocessing sequence (Fig. 3).

Among the advantages of such an approach, the reduced embedded computing capability can be considered preeminent. The greatest part of the mathematics is carried out on a PC with multiple floating-point operations per second, without the stringent requirements of real-time processing. In addition, since data are saved in the rawest possible format, should different or more efficient postprocessing routines be developed in the future, it will always be possible to run them on all previously saved test flight data.

Data are filtered and converted into a convenient format, then subjected to appropriate computation procedures including ADS (air-data system) data processing to obtain altitude, airspeed, and rate-of-climb information; differential GPS augmentation; and GPS and inertial measurement unit (IMU) integration. Concerning the latter, a trajectory reconstruction algorithm has been developed based on an extended Kalman filter that performs satellite and inertial data fusion in tight coupling (Fig. 4). The algorithm displays high accuracy for position, velocity, and attitude reconstruction; it is robust and yields a high output data rate, ensuring data availability even during GPS signal outages.

Further Capabilities

Although not yet fully implemented, the Mnemosine FTI system provides a telemetry capability. Data can be downloaded in real time to a ground station during flight to allow online ground monitoring of the flight-test mission. Requirements set for the design of this subsystem included free use of a radio frequency, a range of a few kilometers, a reasonable bandwidth (100 kbit/s), and adequate reliability. The radio-frequency data link is based on a digitally enhanced cordless telephone, a general radio access technology for wireless communications characterized by frequency-division multiple access (with 10 frequencies between 1880 and 1900 MHz), time-division multiple access, and time-division duplex. The ground station is equipped with PC-based visualization interface utilities and a fuzzy-logic-guided antenna-tracking function. Telemetry range tests have shown the data link to provide good coverage up to a distance in excess of 7 km in line of sight. Although not particularly high, such a range would be sufficient, based on the activities performed to date, for a wide array of missions in flight testing of small aircraft.

Additional sensors for acquisition of structural deformations are currently considered with their corresponding nodes, in view of possible load survey trials. In fact, the current bus load amounts to only 15%, allowing for considerable expansion of the system, including a sizable number of strain gauges to assess wing and tail root loads, landing gear loads, fatigue, etc.

Nando Groppo's Trial Model

Ing. Nando Groppo s.r.l. is a highly reputed Italian ULM manufacturer based in Mezzana Bigli (Pavia). Its product line encompasses several dual-seater, single-engine models ranging from the simple high-wing tube-and-sailcloth construction of Groppino, to various aluminum-built aircraft such as the Dui, the XL, and the Trial.

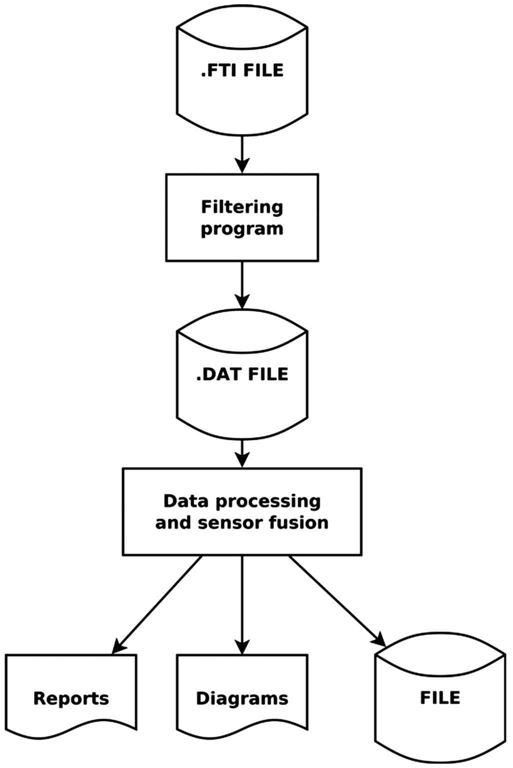

Fig. 3 Postprocessing data flow schematics.

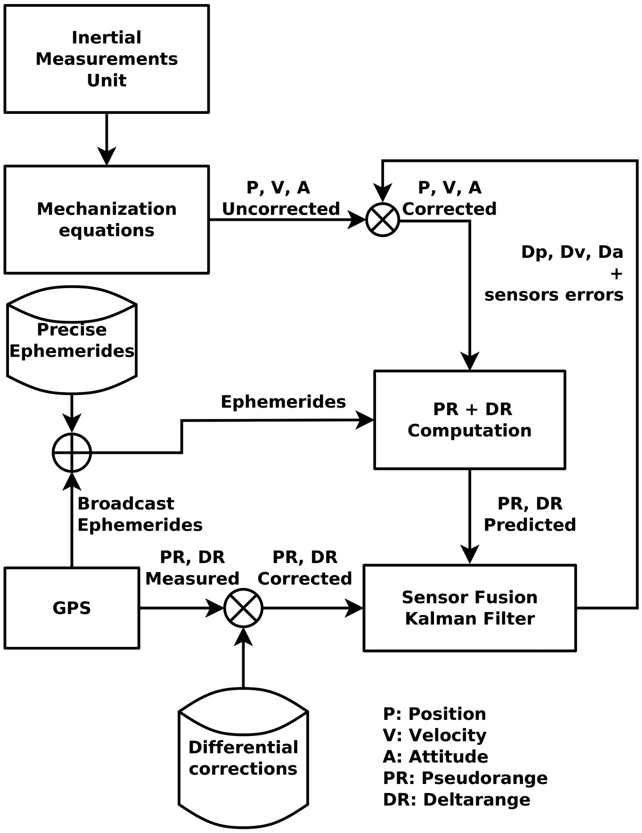

Fig. 4 Trajectory reconstruction algorithm schematics.

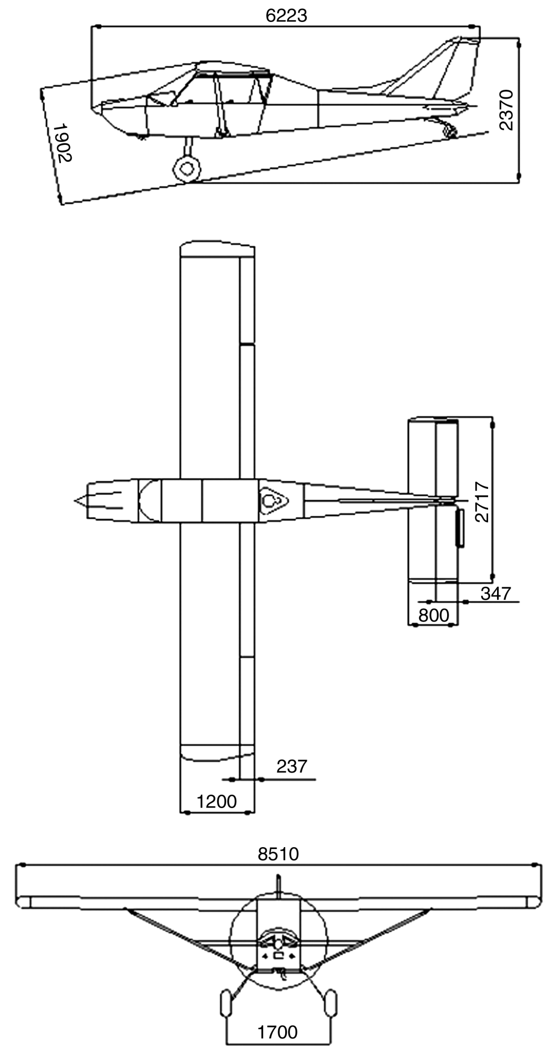

Fig. 5 Three views of the Ing. Nando Groppo s.r.l. Trial model.

The latter is shown in Fig. 5, where all dimensions are given in millimeters. It features a tandem-seat configuration, high wing, and a tail-dragger fixed landing gear. The straight rectangular wing is endowed with flaps and conventional ailerons and was fitted with turbulators on the leading edge for the full wing span. The tail features a classical reverse-T configuration, with conventional elevators and rudder. The airframe is almost fully made of aluminum alloys such as 2024 T3 and 6061 T6, with a limited use of composite materials (in particular, glass fiber is employed for the wing leading edge). The fuselage is particularly slim, given the tandem-seat configuration. Furthermore, the wings are hinged at the root and can be quickly folded alongside the fuselage, greatly reducing the machine front section and thus easing transportation on a trailer car as well as hangaring.

Principal dimensions are reported in Table 3. The considered maximum takeoff weight (MTOW) is 472.5 kg, i.e., the maximum admissible for compliance to the airworthiness requirements, as detailed in the following section.

Primary flight controls (stick, pedals, and throttle) are mechanically actuated, whereas longitudinal trim and flap controls are electrical. All controls are doubled, one for each seat. Basic cockpit flight instrumentation includes ASI (airspeed indicator), altimeter, vertical-speed indicator, engine rpm (revolutions per minute) indicator, ball-slip indicator, magnetic compass, fuel level indicator, oil temperature gauge, oil pressure gauge, and cylinder head temperature indicator.

Powered by either a Rotax or a Jabiru engine in the 80 hp class, it represents a rustic, sturdy (albeit very light), reliable airplane suited for training and recreational purposes, such as cross-country flight. Declared representative performances, summarized in Table 4 [all figures refer to MTOW, International Standard Atmosphere conditions, and sea-level (SL) altitude in the case of the first five items], place the Trial on a par with several Italian and international competitors. Handling qualities are also very good, making the Trial a suitable candidate for flying-school activities.

The specific model subject to the flight-test campaign was powered by a Jabiru 2200 cm^3 engine with a three-bladed, composite, fixed-pitch propeller. The Jabiru 2200 cm^3 is a four-cylinder, four-stroke, horizontally opposed, air-cooled engine capable of delivering a maximum power of 85 hp at 3300 rpm. For safety reasons, the aircraft also features a ballistic recovery system (i.e., a rocket-enabled parachute), which is a mandatory device in some countries.

Certification Basis

Applicable Norms

The certification of the Trial is being carried out according to the LTF-UL 2003 [9] airworthiness requirements for three-axis standard control for ultralight aircraft. These norms, issued by DULV (Deutsche Ultraleichtflugverband) and adopted by the German Deutsche Flugsicherung (DFS) authority, encompass typical light aircraft airworthiness requirements grouped under the following headings: general, flight, strength requirements, design and

Table 3 Principal dimensions of the Ing. Nando Groppo s.r.l. Trial model

Wing span	8.51 m	27.9 ft
Overall length	6.22 m	20.4 ft
Overall height	1.90 m	6.2 ft
Wing surface	10.20 m^2	109.9 ft^2
Wing loading	46.3 kg/m^2	9.5 lb/ft^2
Horizontal tail span	2.72 m	8.9 ft
Main landing gear width	1.70 m	5.6 ft
Cockpit width	0.78 m	2.6 ft

Table 4 Declared representative performances of the Ing. Nando Groppo s.r.l. Trial model

Takeoff distance (on grass, SL)	300 m	984.3 ft
Landing distance (on grass, SL)	250 m	820.2 ft
Stall speed (full flaps, engine idle)	60 km/h	32.4 kt
Maximum rate of climb (SL)	>4 m/s	>787.4 ft/ min
Airspeed for maximum rate of climb (SL)	100 m/s	54.0 kt
Service ceiling	3000 m	9843 ft
Typical cruising speeds	125–170 km/h	67.6–91.8 kt
Maneuvering speed	125 km/h	67.6 kt
Maximum/minimum load factor	$+4\ g/-2\ g$	——
Never exceed airspeed	198 km/h	106.9 kt

Table 5 Conditions demonstrated through flight testing

Test conditions	Applicable standards paragraphs
Stall-speed determination: wing-level idle and power-on, turning	LTF-UL 49, 201, 203 [9]
Takeoff	LTF-UL 51 [9]
Landing and balked landing	CS-VLA 75, 77 [10]
Climb performance	LTF-UL 65 [9]
Longitudinal and lateral-directional control, elevator control forces in maneuvers, trim speed range	LTF-UL 143, 145, 147, 155, 161 [9]
Longitudinal and lateral-directional static stability	LTF-UL 171, 173, 177 [9]
Longitudinal and lateral-directional dynamic stability	LTF-UL 181 [9]
Power-plant cooling	LTF-UL 1041 [9]
ASI calibration	LTF-UL 1323 [9]

construction, power plant, equipment, operating limitations and information, and propeller. These requirements closely match those included in the Certification Specifications for Very Light Aircraft (CS-VLA [10] being a lightened version of CS-23, [11]), which apply to aircraft of a larger size than ULMs.

In particular, LTF-UL requirements apply to ultralight aircraft with a maximum certified takeoff weight of not more than 300 kg for a single-seater and 450 kg for a dual-seater [plus the weight of the additional rescue system (ballistic parachute), estimated as 22.5 kg] and to a stall speed V_{s0} (at MTOW, engine idling, landing configuration) of not more than 65 km/h.

The LTF-UL requirements involve different means of compliance, including calculations, ground tests, and, of course, a number of flight tests. In addition, the CS-VLA regulations concerning landing and balked landing (two flight categories that are not included in the LTF-UL standards) have been considered for the sake of completeness.

Optimized Flight-Test Matrix

The analysis of the LTF-UL airworthiness requirements led to the definition of a flight-test matrix of considerable size in which the different test conditions have been synthesized in terms of weight, c.g. (center-of-gravity) position, flap configuration, landing gear configuration, and trimmed flight conditions. In particular, demonstration through flight testing has been considered for the conditions shown in Table 5.

The analysis led to a total of 397 test points. However, this result has been judged to be fairly oversized with respect to actual needs. Therefore, in accordance with the manufacturer and with the approval of the DULV certification body, the analysis was reviewed in order to get a considerably slimmer campaign, without affecting safety and reliability in any way. Typically, the most demanding conditions in terms of weight (MTOW), c.g. position (maximum forward or maximum aft, depending on the test item), and flap deflection (cruise or landing setting, depending on the test item) have been selected for testing, discarding most of the demonstrations under less exacting circumstances.

Test-point optimization only partially affected the planning for some items such as stall-speed determination and stick-force determination, whereas a drastic reduction was carried out on trim and on static and dynamic stability flight trials. As a result, the optimized flight-test matrix featured 183 test points, i.e., less than 50% of the previous total. This was judged to be an acceptable basis for structuring the flight-test campaign.

Testing the Trial

Flight-Test Campaign

The necessary flight-test missions have been designed gathering multiple test points, based on similarity in altitude, speed range, and c.g. position. Special attention has been devoted to contain pilot workload (particularly in view of the fact that the pilot was not a professionally trained and certified test pilot), designing missions not exceeding 1 h flight time, with limited altitude changes.

As a result, the flight-test campaign consisted of a few dozens flight-test missions, accomplished in slightly more than a week's work (albeit distributed over a much longer time period). Repetition of test points has been contained to a few occurrences, such as for ASI calibration, when a few different locations for the static probe were investigated after the initial placement showed poor performances.

In many missions, the core activities have been preceded and followed by wind speed determination maneuvers, using the GPS cloverleaf method [12]. Most of the missions included takeoff and landing performance demonstration, allowing for reliable performance estimation by averaging across multiple tests.

Adopted flight-test procedures included most of the typical techniques currently employed in testing aircraft in the CS-VLA and CS-23 categories. For example, air-data system calibration has been carried out following the National Test Pilot School GPS horseshoe heading with averaging method [13]; stall speeds have been determined by averaging across several standard 1 g quasi-steady decelerations; takeoff and landing were considered in terms of performances, controllability, and pilot workload; sawtooth climbs have been carried out to assess specific excess-power characteristics; windup turns have been used to determine stick-force gradients with respect to load factor; and longitudinal stick and pedal doublets have been used to assess dynamic stability.

In all flight-test missions, relevant parameters have been measured and stored by the Mnemosine FTI system permanently installed onboard. Under the need to provide piloting stick-force data, the system was endowed with a biaxial slip-on load cell knob by Futek, a sensor originally developed for gearshift force measurement in automotive applications. Flight control position has been acquired by means of a pair of string potentiometers, used for the stick, and a pair of linear potentiometers, used for the pedals.

Fig. 6 Some elements of the Mnemosine FTI system onboard the Trial.

The various sensors and transducers as per the previous description have been mounted with minimal impact on the internal ergonomics. Figure 6 shows some elements of the system installed in the vicinity of the front seat, the biaxial force sensor mounted on the stick head, the attitude and heading reference system placed between the pedals, a rack stacking several acquisition nodes fixed to the frontal bulkhead panel, and the data recording unit secured on a diagonal stiffener of the left panel. To guarantee maximum safety, the installation of the system has been carried out in close collaboration with the aircraft designer and manufacturer and the pilot.

Several flight missions were performed with an additional ADS employing a Rosemount pitot boom (Fig. 7, composed by the pitot static tube P/N 852AG, two flow-angle sensors P/N 861E2, and a total-temperature sensor model 102KH4DR), providing static pressure, dynamic pressure, angle of attack and angle of sideslip measurements. This massive (and expensive) device has been made available to DIA-PoliMi courtesy of Alenia Aermacchi, but can be substituted by several different models of much lighter and less expensive pitot booms that are available on the market. In any case, the modularity of the FTI system allows for switching from the basic airplane ADS to a FTI device by simply connecting the pressure lines from the Urania node to the corresponding sensor, without further hardware or software operations, once the calibration of both instruments is available.

Fig. 7 FTI pitot boom installed below the Trial right wing.

The impact of the FTI system on the vehicle was indeed very low. Given that the total weight of the Mnemosine system, pitot boom excluded, stands below 5 kg, the FTI installation did not represent a particular concern with respect to weight limitations. Total power consumption amounts to 9 W.

Flight data were usually postprocessed on a laptop PC in preliminary form immediately after the mission completion, within 10 to 15 min, to support debriefing and preliminary assessment. In a few cases, on-the-fly data analysis has shown the need to repeat some test points or to improve the flight-testing technique, suggesting practical hints to the pilot. The system displayed a remarkable level of overall reliability. In fact, data loss occurred in only one mission, due to unnoticed physical disconnection of the data bus on the Klios storage node.

It must be remarked that the flight campaign took considerable advantage from the concurrent flight activities of the flight-testing course scheduled in June 2010, close to the end of the classes. A synergic approach putting together the needs of the certification and didactic activities allowed missions to be performed that proved to be valuable toward both ends. Most of the missions were thus performed with a two-person test crew, with the second person being a graduate student specifically trained, within the scope of the present activities, to act as a FTE. In double-crew missions, the test pilot workload was significantly reduced with respect to single-crew conditions, and enhanced situation awareness was achieved.

Discussion of Results

The overall performance of the Mnemosine FTI system in the present activity can be assessed as being fairly satisfactory. Time histories of some 30 parameters were thoroughly recorded during a considerable number of flight hours, allowing postflight preliminary verification and complete offline postprocessing. The current raw binary data flow rate onboard amounts to about 1 Mbit/min. This translates into a size of the recorded file for each flight typically ranging between 20 and 50 Mbit. Postprocessed data file size is inflated by a factor of 10.

A top (event marker) counter was used to identify single trim points and maneuver durations, easing the task of isolating specific sections from the full data streams. The top-counter functionality has been integrated in the Melpomene node (the command and display unit) with its button switch and a display of its current value. The top-counter event is included in the acquired parameter list and, as such, is time-stamped with the CAFFE procedure and evaluated during the offline postprocessing.

A first positive outcome has been the successful relocation of the static pressure ports from under the left wing, where the airplane total pressure probe is placed, to the sides of the fuselage just before the front cockpit. This modification was in order to comply with the ASI airworthiness requirements and was supported by velocity measurements from the Terpsicore GPS node. Further activities have involved verification of the Trial air-data system in comparison with the FTI pitot boom fitted to the aircraft, which featured an error in calibrated airspeed (CAS) under 2% with respect to the corresponding quantity obtained through GPS.

Eventually, all the certification requirements that needed in-flight demonstration were assessed, showing compliance with the relevant LTF-UL and CS-VLA standards. A few items concerning control, trim, and stall characteristics needed repetition, due to unsatisfactory results collected in the first trials. These typically concerned precision of maneuver (e.g., precise trim shot) and correct execution of the test technique (such as adequate control rate) and were greatly affected by significant atmospheric instability typically encountered on hot days. Completion of the flight-test matrix was finally accomplished in August 2010.

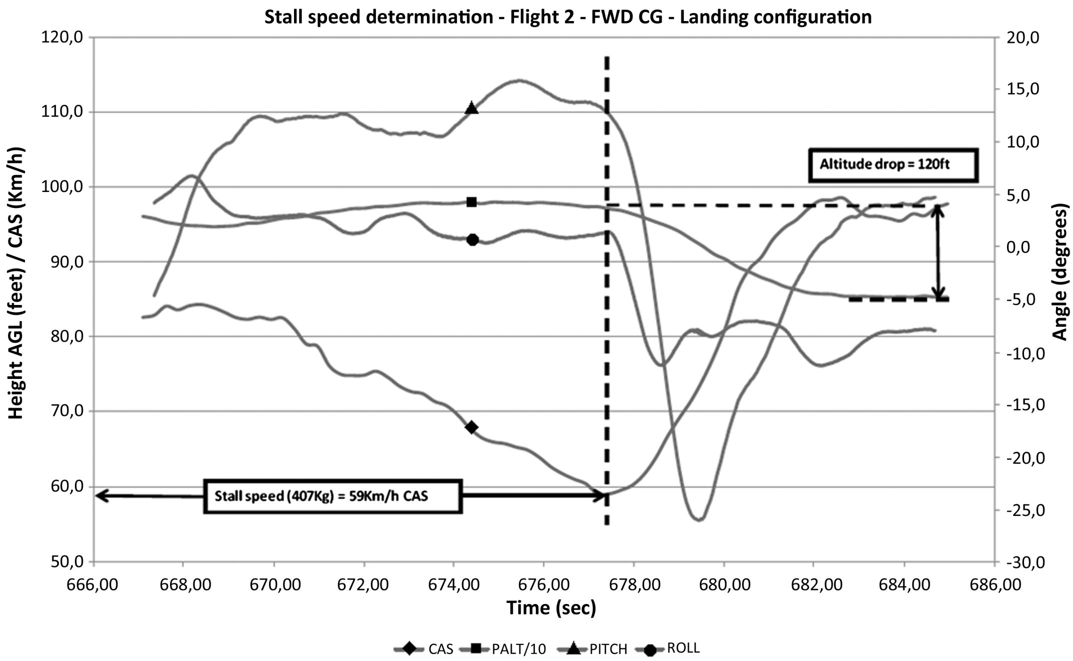

Fig. 8 Time histories during a stall test (courtesy of Ing. Nando Groppo s.r.l.).

A comprehensive flight-test report has already been submitted to DULV, in partial fulfillment of the requirements for the Trial LTF-UL certification, receiving praise for the depth and range of the performed analysis, as allowed by the wealth of data gathered from the Mnemosine FTI system.

As an example of the quality of the performed analyses, Fig. 8 shows the CAS (diamond), pressure altitude (square), pitch (triangle), and roll (circle) time histories during a stall test in landing configuration, with maximum forward c.g. position. CAS values in km/h are given on the left axis, as well as pressure altitude values in feet divided by a factor 10, and pitch- and roll-angle values in degrees are given on the right axis. Pitch break, roll behavior, altitude loss, entry deceleration, and other significant characteristics can be easily observed. After checking against several analogous results, it appears that the behavior of the airplane is symmetric and fairly benign and that elevator control is sufficient. Adequate stall warning in the form of slight buffeting has also been observed.

Another example is shown in Fig. 9, where height above ground level (square), CAS (diamond), and normal load factor (circle) time histories are plotted for a typical takeoff maneuver. Height values in feet and CAS values in km/h are both given on the left axis, and normal load factor values are given on the right axis. In these trials, the takeoff procedures employed were both the recommended three-point technique, allowing the aircraft to lift off the ground spontaneously at the appropriate speed, and the conventional technique, where the pilot lifts up the tail during the ground course before rotation to liftoff. In both cases the aircraft behavior was judged to be excellent and fully compliant with the relevant requirements.

A further example is given in Fig. 10, where elevator deflection and longitudinal stick force are plotted around different values of trim airspeeds to demonstrate positive longitudinal static stability. For each case, trim conditions were maintained in stick-free mode for several seconds, before applying a pull or push to the stick to stabilize a new airspeed. Three trim airspeeds are considered: 120, 140, and

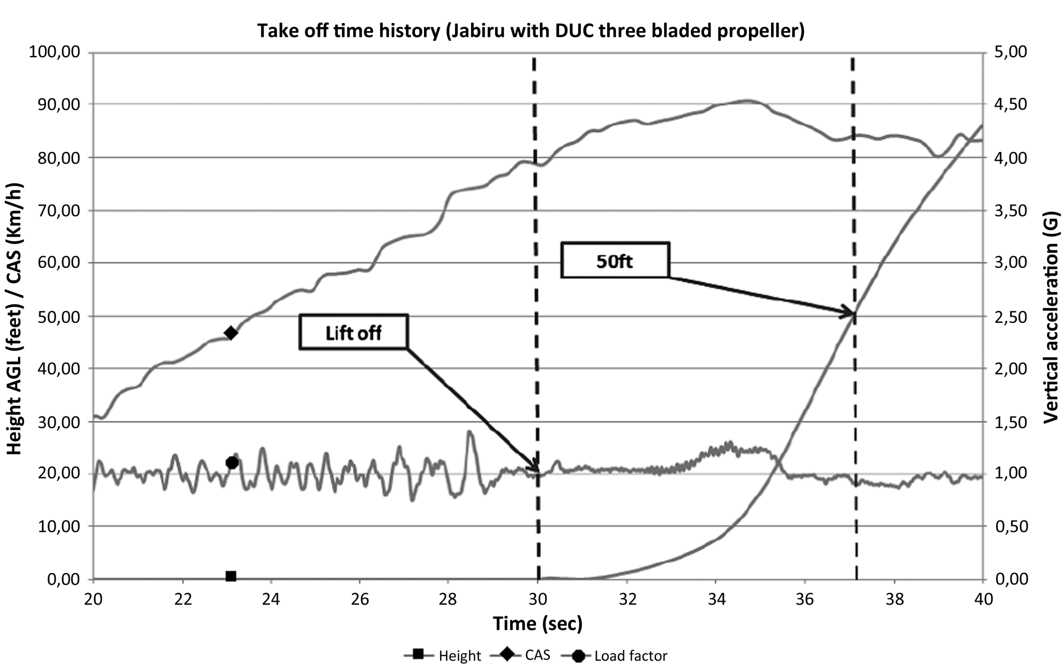

Fig. 9 Time histories during a takeoff test maneuver (courtesy of Ing. Nando Groppo s.r.l.).

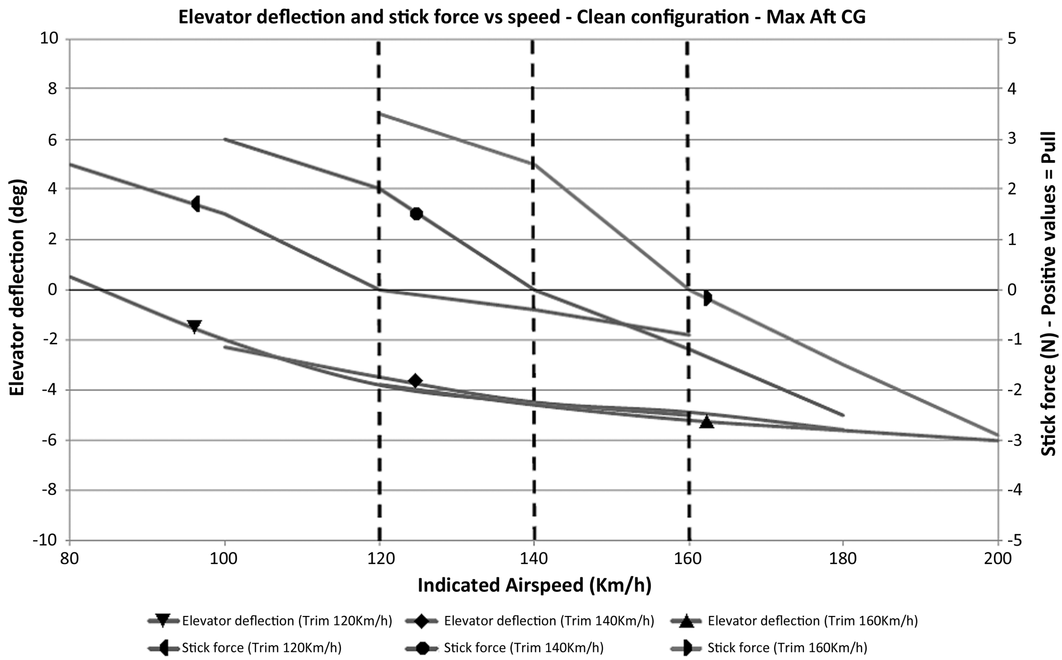

Fig. 10 Longitudinal static stability assessment in the neighborhood of three trim airspeeds (courtesy of Ing. Nando Groppo s.r.l.).

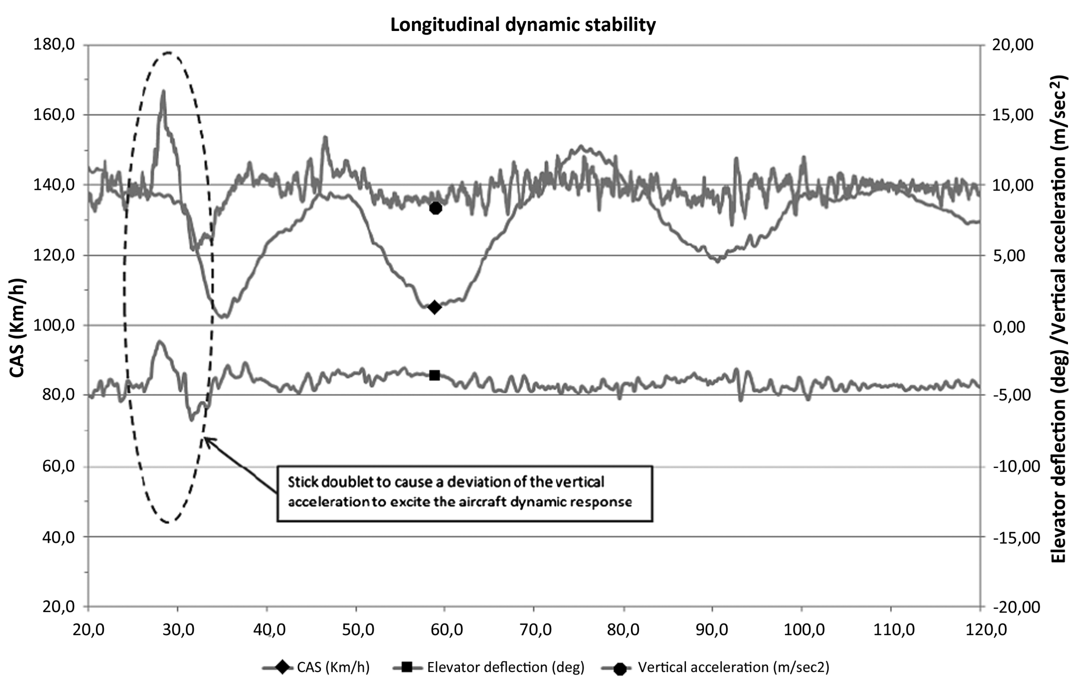

Fig. 11 Time histories during a longitudinal dynamic stability test (courtesy of Ing. Nando Groppo s.r.l.).

160 km/h. Elevator deflection angles measured while perturbing the equilibrium at each of the three airspeeds are given by the curves identified by the following symbols: triangle pointing downward, diamond, and triangle pointing upward, respectively. Values are given in degrees on the left axis. Corresponding longitudinal stick forces are given by the curves identified by the following symbols: left half-circle, full circle, and right half-circle, respectively. Values in N are given on the left axis (positive values correspond to stick pulling). As apparent, these quantities display a substantially regular, almost linear, behavior with the necessary negative derivative with respect to airspeed. Piloting forces were found to be very light in all investigated conditions.

Finally, in Fig. 11 we show an example of time histories for CAS (diamond), elevator deflection (square), and vertical acceleration (circle), corresponding to a control-fixed longitudinal dynamic stability test performed by exciting the aircraft dynamics through a stick doublet at the trim airspeed of 140 km/h. CAS values in km/h are given on the left axis, and elevator deflection angle values in degrees and vertical acceleration values in m/s^2 are both given on the right axis. Center-of-gravity position was maximum aft. Overall, the longitudinal and lateral-directional dynamic responses of the airplane were found to be stable on all axes and, especially, damped with respect to short-period motions.

Conclusions

The described activity can be considered remarkably successful: Politecnico di Milano's educational needs, related to its unique flight-testing graduate course and to several M.S. thesis projects, have been synergically matched with the certification requirements of a leading

Italian ULM manufacturer, yielding a comprehensive flight-testing campaign for the Ing. Nando Groppo s.r.l. Trial model, aimed to its type certification according to the German LTF-UL airworthiness requirements. The flight-testing process was completed in a matter of weeks, related documents were provided to the certification body, and the certification procedure was successfully finalized in January 2011. Several graduate students have been directly involved in the activity, receiving hands-on experience in the role of flight-test engineers.

In this unique, safety-inspired, affordable, and reliable approach, the DIA-PoliMi Mnemosine FTI suite has shown full compliance with its design requirements as well as the certification needs. Apart from some minor glitches to be ascribed to inexperience, the students interacted easily and effectively with the instrumentation, in spite of their short training. The completion of the testing activity was carried out by Ing. Nando Groppo s.r.l. personnel, who did not need any lengthy special training to operate Mnemosine and postprocess its data.

The raw cost of a single set of the Mnemosine FTI suite in the current configuration is below €10,000. Nonrecurring production costs are estimated below €5000. Therefore, the FTI system fully supported the analysis necessary to demonstrate compliance with severe airworthiness standards, with actually sustainable global costs, which is a real breakthrough given the considerable investments traditionally related to flight testing, which consequently represents a typical prerogative of major companies involved in aircraft classes that are larger than ULMs.

As of today, Mnemosine has been permanently installed on three different ULMs (DIA-PoliMi's P-92, Ing. Nando Groppo s.r.l. XL, and Ing. Nando Groppo s.r.l. Trial) requiring very little modifications, and due to its low intrusiveness, it has been still possible to use the aircraft for ordinary, non-flight-test-related activities. Mnemosine has been used in over 100 flight-test missions to date, showing adequate reliability and performances. This system supported the laboratories of the flight-testing course in the past six years. Given the current low bus load level, the system has a considerable growth potential. Migration to light gliders and larger general aviation aircraft is currently under consideration.

Several improvements are currently under consideration, building on the feedback obtained during the described flight-test campaign. Among these, the next-generation FTI hardware, currently under development, will feature a modified architecture designed to bring additional volume, weight, and power consumption benefits by collapsing the functionalities of a number of separate nodes (e.g., GPS, IMU, data logging) that are constantly present onboard into a single supernode. A further enhancement concerns empowering the Melpomene node (the command and display unit) to display test-point-relevant data to the FTE in real time, in addition to the top-counter current value. Wireless data communication extensions are also considered, as well as full integration of the telemetry capability, possibly extending its range.

With respect to improving flight safety, in addition to cost-effective support for type certification, some characteristics of the Mnemosine FTI suite (namely, its reliability, compact size, and low cost) suggest a further opportunity: to maintain a suitable subset of the instrumentation aboard an aircraft (for example, aero-club-operated machines rented for flight training and/or leisure flying) in order to monitor normal flight operations. This may also positively impact safety in the ULM environment, where the pilot community is much more heterogeneous with regard to training and experience than that operating in other segments of aviation. In the long run, this could lead to building a reliable knowledge base concerning the actual usage of this kind of aircraft, suggesting guidelines for improvements in design and operating procedures.

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