IEP: A MULTIDISCIPLINARY FLYING TESTBED FOR NEW AIRCRAFT CONCEPTS

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Abstract

The European project NACRE (New Aircraft Concept REsearch) enabled a team of research centers and universities to develop a demonstrator for a new test facility called Innovative Evaluation Platform (IEP). Investigations were planned in noise assessment, stability and control parameters identification and analysis of recovery procedures in case of hazardous flight conditions. The test technique consists in performing various flights with a testbed that is a dynamically scaled model of a future concept aircraft. Because of the specific characteristics of the system, analyses based on the in-flight measurements can be extrapolated to full scale concept. Following an initial feasibility study where possible assets of such an approach in comparison to existing methods have been identified, the consortium carried out the complete design and manufacturing of the IEP with emphasis on its acoustic capabilities. With the objective of minimizing risk, the consortium completed an extensive verification and validation phase before the delivery of the system. Subsequently, the experimental flight test campaign has been prepared with a step by step strategy leading to the qualification of the IEP for measurement missions.

List of acronyms

GCS	Ground Control Station
HFC	Hazardous Flight Conditions
IEP	Innovative Evaluation Platform
MFP	Modular Flying Platform
NACRE	New Aircraft Concept REsearch
SPL	Sound Pressure Level

1 General Introduction

NACRE (New Aircraft Concepts REsearch) is an Integrated Project led by Airbus with a consortium of 36 partners from 13 countries and partly funded by the European Commission under FP6. During this project, technologies and design capabilities at the component level (lifting surfaces, powerplant installation, fuselage) have been developed and integrated within novel aircraft concepts (Pro Green Aircraft, Payload Driven Aircraft, Simple Flying Bus) to achieve air travel affordability, environmental performance and air transport efficiency. To assist engineers in the design of these components and associated future configurations, NACRE proposed in Task 1.4 to develop a demonstrator for a new test facility based on a flying platform: the Innovative Evaluation Platform (IEP). This IEP would be in particular used to investigate six areas of interest for new aircraft concepts: high-lift devices, flight dynamics, recovery from Hazardous Flight Conditions (HFC), noise assessment, wake vortices and laminar flow studies. In the project, the IEP could have many forms such as a full scale aircraft with modifications for some parts, but it appeared early in the study that a scaled version of a new aircraft has the largest potential to reduce costs and deliver valuable data.

Carried out by a team of research centers and universities, the development has been divided into the following subtasks:

- T1.4.1: IEP assessment and feasibility
- T1.4.2: IEP design and manufacturing
- T1.4.3: IEP tests

The goal of this paper is to review all activities completed by the partners during the project with a focus on specific studies regarding acoustics.

2 IEP assessment and feasibility

In Subtask 1.4.1, the partners had to assess the relative merits of the IEP in comparison to conventional test facilities including technical, operational and economical aspects. Thus, a multicriteria approach in four steps has been followed. Details of the work done in T1.4.1 are available in [1].

First, a technical assessment and a cost review of the existing test practices (divided into three categories – free models, fixed models and numerical tools) have been carried out. In this manner, a reference database has been generated to assess the competitiveness of the IEP as a test facility.

Second, the partners explored for each discipline of interest the possible benefits of having a flying platform dedicated to measurements. In parallel, basic requirements to be met by the IEP in order to gain valuable knowledge during the experiments have been identified. Since some areas of interest had extremely stringent requirements on the system, it has been decided to only focus on three domains: noise assessment, stability and control parameters identification (under the area of interest "flight dynamics") and recovery from HFC. In the end, to have full view of the IEP assets and drawbacks, a first cost and operational assessment has been completed.

Conclusions from the previous phases have been used afterwards to propose different IEP concepts and proposals. A key element at this point has been the idea to implement the modularity of a wind tunnel model to a flying platform that represents a scaled future concept with the objective of testing several aircraft configurations having the same primary structure. Also, after an analysis of the various disciplinary constraints, a unique IEP system investigating several disciplines has been proposed. This system consists in two main components, the Modular Flying Platform (MFP) and the Ground Control Station (GCS).

The MFP is an unmanned platform which configuration can be easily changed through a modular structure [1]. On the ground, an external pilot with direct view on the MFP is remotely controlling the manoeuvres at takeoff and landing through a radio link.

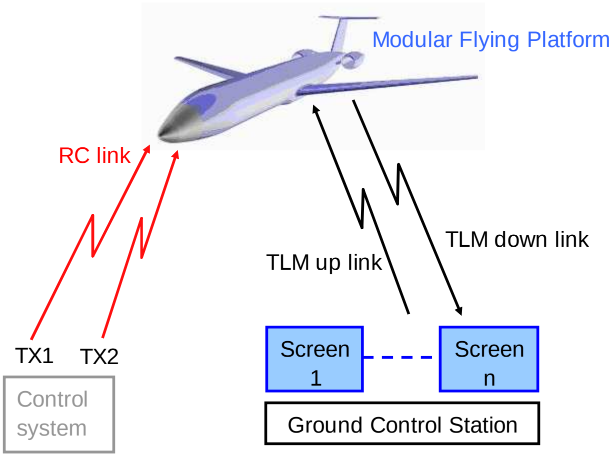

Fig. 1. IEP description sheet

Engineers working on the GCS support the pilot with real-time information coming from the MFP and displayed on several screens. For the in-flight investigations, an autonomous mode is turned on and the MFP can perform pre-programmed manoeuvres defined by disciplinary experts. Subsequently, the post processing of the recorded data during the manoeuvres enables the aircraft parameter identification as well as the assessment of recovery procedures from HFC. For noise, it is planned to have the MFP flying over microphones with 2 different tail geometries. Comparison of the acquired measurements would assess amongst others the shielding capabilities of each airframe architecture.

As last step of T1.4.1, the partners completed comparison matrices to identify some trends when comparing an existing facility with a possible IEP. Results of this comparison showed that an IEP under the form of a flying scaled platform offers potential benefits in terms of new technical capabilities, higher flexibility and lower costs. However, the design of the IEP must meet stringent requirements to achieve valuable measurements. Because of this positive conclusion at the end of the first task, it has been decided during a Critical Design Review to initiate the IEP design and manufacturing.

3 IEP design and manufacturing

Before starting the second phase of the project, all partners iterated to agree on a unique definition of the system to be built based on the project constraints and the capabilities of the different entities:
"The IEP is a competitive test facility based on the use of a Modular Flying Platform that is a scaled version of future aircraft concepts enabling:

- identification of stability and control parameters;
- noise assessment;
- analysis of different recovery procedures in the case of Hazardous Flight Conditions"

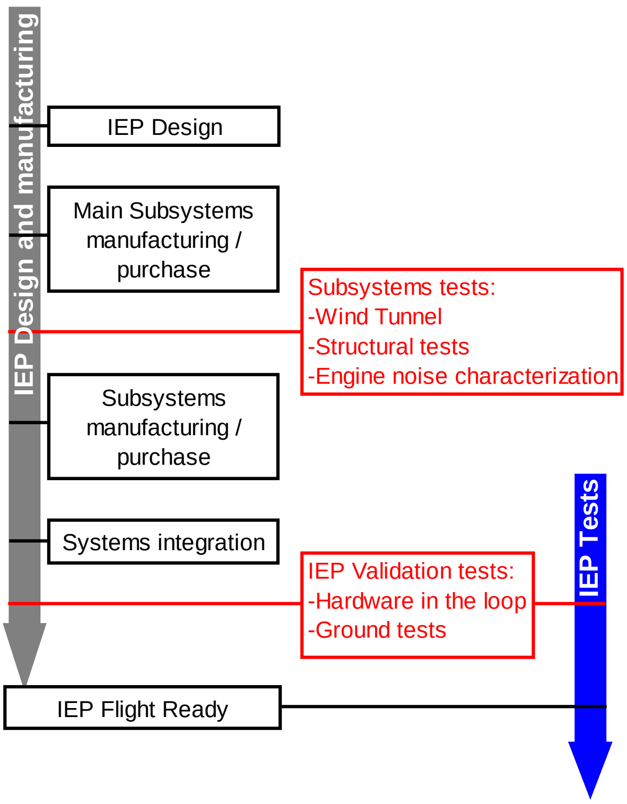

Fig. 2. Design and manufacturing process

With such a complete definition of the system to be developed, the partners followed the standard phases illustrated here above to have a safe, reliable and affordable system.

The design process, based on a requirement analysis is divided into the classical three steps: conceptual, preliminary and detail design. For all three stages, the fidelity level of the methods and tools has been selected in order to maximize the scientific gain with respect to the invested time. After several iterations to answer all requirements, the team converged to a final design of the flying testbed. With the IEP design frozen, the team started the manufacturing of the airframe parts (Politechnica Warsawa), purchased basic components such as engines and developed an early version of the avionics. Following the completion of the full airframe, T142 partners carried out different verifications such as wind tunnel tests to validate the design. With a validation of the system main components, the design team went on with the manufacturing and purchase of subsystems such as the landing gear. Then the final integration of all systems has been completed at the University of Stuttgart. The final phase of the process indicated as "IEP validation tests" is the transition phase between subtask 1.4.2 and subtask 1.4.3: it corresponds to the final validation of the system before its delivery to the test team.

3.1 Requirement analysis and conceptual design

Because of the nature of the system, the requirement analysis has been a challenging task. The IEP is indeed a flying test facility and there are several conflicting requirements. The design team decided then to recognize at first requirements directly linked to the IEP system and its unmanned vehicle like architecture. In a second step, requirements related to the disciplinary measurements to be carried out in flight have been identified. The complete requirement analysis presented in [1] ended with the generation of two compliances matrices driving all steps of the design.

The conceptual design started with the definition of the MFP configuration. With the objective of assessing a new aircraft concept with limited development risk, the design team decided to use a reference architecture with a U-Tail empennage inspired from the Pro Green Aircraft. From this baseline, it has been decided to aim for a design offering the possibility to change the main components of the MFP such as wings and fuselage. Given the project budget, the team decided to validate this modularity concept by focusing the design and manufacturing on a second interchangeable T-Tail empennage. With this decision, the design team reduced design issues by maintaining the propulsion system of the aircraft in the same area and gave the possibility to acoustic experts to compare the actual noise shielding of the two solutions. The next figure illustrates the modularity aspects of the MFP.

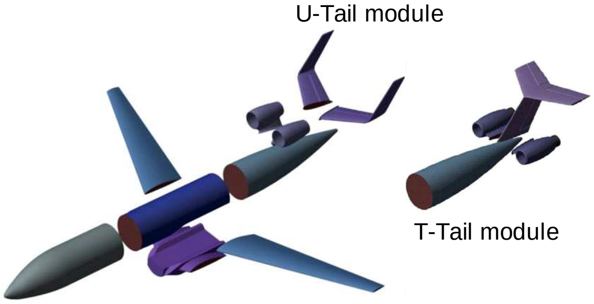

Fig. 3. MFP modularity

It is important to note that in order to assess landing gear noise, the design team decided to integrate a retractable landing gear within the MFP. The complexity of this subsystem has been increased since its installation had to meet the modularity requirements between the wing and the fuselage. Once the general architecture was set, the sizing of the MFP has been based on:

- the necessity for the airframe to meet the Froude similarity in order to be able to extrapolate conclusions from the IEP flight tests to full scale future aircraft;
- the characteristics of the available jet engines on the market in terms of performance and reliability;
- the operational aspects, knowing that the ground pilot must have a constant eye contact with the MFP.

The result is an aerial vehicle of about 145 kg with both a wingspan and length of about 4 meters and two engines producing a maximum thrust of about 210 N each.

Concurrently with the MFP conceptual design, engineers paved the way for the design of both the GCS and the avionics. The main effort for the Ground Control Station design was the development of software capable of running on a network of computers and enabling the addition of measurement modules according to the tests. Regarding avionics, early design stages assessed the impact of the modularity requirements and identified the necessity of a modular architecture to be able to have different sets of airframe components connected to the same on-board computer.

3.2 Preliminary / detailed design and manufacturing

The preliminary and detail design of the Innovative Evaluation Platform have been an important milestone of the project. Work carried out during theses phases is presented in [2] where validation steps are also detailed.

3.3 Specific features related to noise assessment

The possibility to assess noise through a flying testbed in a real atmosphere is a key asset of the IEP. The conventional procedure to validate aircraft noise estimates during a development phase is to measure scale model noise during open section anechoic wind tunnel tests and project the data to full scale by applying the flight effects. Noise measurements of the flying IEP takes away the need to compensate for some of the effects and therefore has advantages such as the absence of a free shear layer. By using the IEP, a Flying Scaled Model, far field noise measurements will produce test data with realistic propagation effects (Doppler frequency shift, ground reflection, spherical spreading and atmospheric absorption). This section details the various studies and developments carried out by NLR with the assistance of University of Stuttgart during the design and validation phase to enhance the capabilities of the system for acoustic investigations.

A major question that is to be answered to for a new concept aircraft is: what is the expected noise footprint on the ground?

For the noise foot print on the ground, important parameters are the type and installation of the engine on the aircraft and the noise generated by high-lift devices and landing gears. Within the project, the potential to answer these questions with an IEP has been studied. A first question was whether scaling laws exist for noise generation. These scaling laws have been identified for different noise sources on an aircraft and listed in Table 1. The modularity of the IEP enables to compare different aircraft concepts for the implications of engine installation including engine noise reflection and shielding by airframe parts. The engines installed on the IEP were characterized in order to assess these differences in flight tests.

On-board noise instrumentation

To meet various requirements for noise assessment, NLR designed specific equipment to be installed on the MFP in order to:

- measure the noise impact on the fuselage from the engines with two microphones installed at the surface of the fuselage;
- generate a sufficiently loud noise through a piezo-speaker to be measured by microphones installed on the ground during fly-overs.

The equipment consists of transducers, loudspeakers, amplifiers, signal conditioning filters and a PC104 computer with an analog data acquisition / analog output card. Connected to the Flight Management and Control System of the MFP, the on-board noise instrumentation can be controlled from the Ground Control Station at any time during the flight. Since this system is used only for acoustic tests, it has been integrated in the MFP in such a way to facilitate its removal to reduce weight.

Scaling of following phenomenon			**Often practiced scaling law**	
Airframe noise	Frequency scaling	Strouhal number	$St = \frac{D}{V} f$	D = a typical length scale of sound generating mechanism V = a typical flow speed
Airframe noise	Sound Pressure Level	Noise level (general)	$SPL = 10.^{10}\log[U^{\eta} \frac{LD}{r^2}] + K$	L = a typical length scale U = flow speed
Airframe noise	Sound Pressure Level	Trailing edge	$SPL = 10.^{10}\log[U^{\eta-0.2} \frac{L^{1.8}}{r^2}] + K$	L = length boundary layer U = flow speed
Airframe noise	Sound Pressure Level	Vortex-shedding	$SPL = 10.^{10}\log[U^{\eta} \frac{L^2}{r^2}] + K$	L = cylinder diameter U = flow speed
Airframe noise	Sound Pressure Level	Cavity noise	$SPL = 10.^{10}\log[U^{\eta} \frac{L^2}{r^2}] + K$	L = cavity depth U =sound speed
Engine noise	Frequency scaling	Inlet and exhaust	$f_{full-scale} = Sf_{scaled-model}$	S = model scale factor
Engine noise	Frequency scaling	Propellers	$RPM_{full-scale} = S * RPM_{scaled-model}$	S = model scale factor
Engine noise	Frequency scaling	Jet noise	$St = \frac{D}{V} f$	D = diameter nozzle V = jet exit velocity

Table 1. Scaling laws applicable for noise

Other parameters essential for noise assessment flight tests are aircraft position, including height and aircraft configuration. These parameters are measured in the IEP with the standard instrumentation system.

Engine noise characterization

One of the IEP objectives is to be able to evaluate the propagation of noise in real atmosphere by recording the noise level on the ground. In this case, however, specialists need to know the noise generated by the source to limit uncertainty during the analysis. It has thus been decided to perform a full characterization of the acoustic properties of the JetCat P200 in the KAT, NLR's small anechoic wind tunnel. The test chamber is 5.5 x 5.5 x 2.5m^3 large and walls are covered with 0.5 m foam wedges, yielding 99% absorption above 500Hz. With the circular section nozzle, of 0.5m diameter, a maximum flow velocity of 75m/s can be attained.

The first series of test enabled to measure data about the engine characteristics in a stationary flow. In this set-up, the engine is located in the center of the test section at a height of 1.35m. Microphones were placed on an arc around the engine at a distance of 2m from 0° (on the rotation axis of the engine, to the front) to 160°, all at a height of 1.35m. To verify the axisymmetry assumption for the noise emission, an additional microphone has been placed on the other side of the jet at 220°. The figure here below illustrates the experimental set-up:

Fig. 4. Experimental set-up for stationary engine tests

The comparison between measurements recorded by microphones located at 140° and 220° shows differences in the order of +/-1 dB in the range between 300 Hz and 20 kHz. The hypothesis of axisymmetry noise emissions is herewith confirmed.

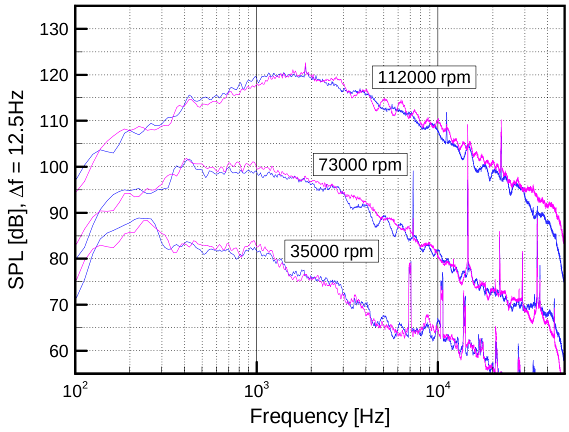

Fig. 5. Spectra at 140° and 220° for different engine regimes

With the same wind tunnel configuration, the overall sound pressure level at each microphone position has been assessed. The next figure represents the data as a function of the emission angle:

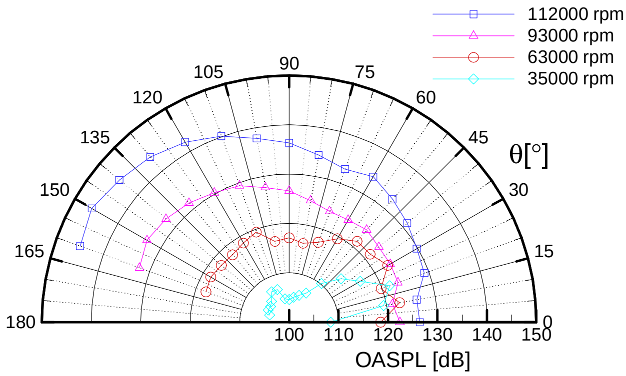

Fig. 6. Directivity plot for different engine regimes

Two different noise emission patterns can be observed depending on the engine setting. For 35000 rpm, sound is radiated mostly in the forward direction at 25° with a level of 122dB. As the thrust setting is increased, the emission pattern changes with a higher level of noise at the rear. For 112000 rpm, 146dB are reached at 150°. This pattern is very common to jet-engine.

Further data processing led to the definition of the narrow band spectra at different positions for various regimes. The tones are identified as the shaft frequency, the blade passage frequency and the 2nd harmonic. The radiation pattern was analyzed for the dominant tones: results indicated a preferred emission angle in the rearward direction for the tone at the shaft frequency while an irregular pattern is found for the other tones.

The NLR team also measured the emission of the piezo-speaker to be installed on the MFP in the no-flow condition. The result is shown in Figure 7.

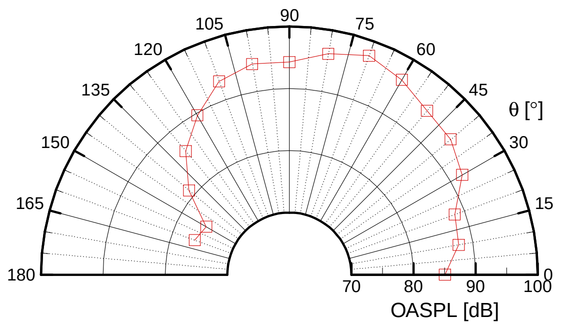

Fig. 7. Directivity pattern of the emission of the piezo-speaker at 5000 Hz

The piezo-speaker has a preferred emission direction (70°) with a sound pressure level of 98dB. However, a decrease of the noise level in the rearward area implies a lack of symmetry in the directivity. The radiation pattern appears to be sensitive to the installation of the piezo-speaker and consequently the noise will only be distinguishable over a limited range of view angles. Regarding this noise level, experiments showed that the piezo-speaker can only exceed the noise generated by an engine in idle conditions. These results were carefully reviewed during the preparation of the flight campaign in order to have the best set-up for in-flight noise measurements with the IEP: the loudspeakers will be used during descents over the ground microphones with the engines in idle thrust setting.

The second series of tests in the KAT has been performed with the objective of assessing noise in the case of an engine immerged in airflow and evaluating the effects of nacelles. In this case, the engine has been moved closer to the wind tunnel nozzle and microphones have been installed on a straight line enabling the recording of sound emissions at angles from 90° to 150°. Figure 8 shows the installation in the test chamber.

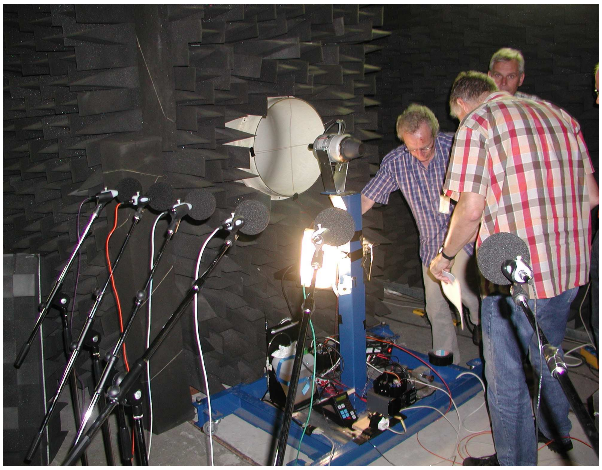

Fig. 8. Experimental set-up for in-flow engine tests

After some tests to verify the reliability of the installation, the test team recorded all data from the microphone for different speeds with the engine at full throttle. Investigations based on the recorded data showed that an increase of the free stream velocity leads to a decrease of the jet sound emission. Regarding the nacelle, its impact on the sound emission is small and noticed only in the region perpendicular to the engine where the Blade Pass Frequency tone is shielded.

The noise of the IEP engine in general has quite a high similarity with a real-scale aircraft engine. The higher frequencies produced by the IEP engine compared with the frequencies of the full scale engine are an asset in view of the scaling laws as given in Table 1. The noise level of the engines is high and limits the assessment of airframe noise or the use of the loudspeaker.

4 IEP experimental campaign

4.1 Overall strategy

The goal of the experimental campaign is to safely demonstrate the capabilities of the IEP prototype to perform a series of valuable measurements in different disciplines. In order to minimize risk during the tests, three subsequent phases have been defined leading to the acquisition of in-flight data for specific investigations.

Validation of Airworthiness
The objective of this step is to complete ground tests on the integrated IEP to complete the verification and validation plan. Starting with "Hardware-in-the-loop" tests during which the full IEP and its systems are connected to a simulator feeding the on-board computer with air data, this validation will be concluded by taxi tests. This verification and validation work is not finished and only after this can the test team consider that the IEP is "airworthy" and that the first flight can be made.

Validation of Mission Suitability
The first flight, also called "shake-down" flight will initiate the validation of the mission suitability. During this phase, the test team will both verify different aspects of the IEP system and validate it as a test facility. Following the first flight carried out in a pilot-controlled mode, several flights dedicated to performance are scheduled. Through these flights, the test team will acquire more knowledge about the MFP behavior and will improve the tuning the autopilot. Afterwards, flights will concentrate on the verification, improvement and validation of the semi-autonomous and autonomous modes. Then, at the end of this second stage, the IEP will be considered as fully capable of performing missions for disciplinary investigations.

IEP Measurement missions
The third phase corresponds to the operational phase of the system during which the measurement missions are carried out. After iterations between the partners considering risk and priorities, it is decided that operations will start with flights dedicated to noise assessment. After all exit criteria will be met, the test team will switch to missions for stability and control parameter identification. Regarding flights focusing on the recovery procedures from Hazardous Flight Conditions, they will occur at the end of the test sequence given the associated risks.

4.2 Flight test preparation

With the overall strategy fixed, the test team prepared in a detailed manner all tests to be carried out during the three phases presented earlier.

Taxi tests have been defined according to common practices in the industry [3] in order to map with a progressive approach the ground handling and the braking capabilities of the MFP. Runs have been thus planned with a step by step increase of speed and weight. The test matrix also included One Engine Inoperative runs to increase knowledge about the aircraft behavior in critical conditions.

Before defining flight missions, T143 partners verified both the performances of the aerial vehicle with 6 degrees of freedom models and the operational envelope of the system (future works are scheduled to consolidate this verification relying on refined models). With this information and a safety constraint requiring a first flight in a range of 1000 meters from the pilot, the shakedown flight path has been defined. The goal in this case is to allow the pilot to get a certain confidence with the system by performing level flights at different speeds, various turns radius and simulated landing approaches. Next flights validating the mission suitability of the IEP have been defined in order to:

- Assess level flight performance and sensors calibration
- Assess climb performances (sawtooth climbs)
- Set-up the Autopilot (stability and navigation)

For this latest series, tests aim at activating one after the other, all controllers and verifying their capability to follow the desired command.

With the IEP system validated for disciplinary investigations, the test team will start flights dedicated to noise assessment. These flights, proposed by disciplinary experts enable the measurement of perceived noise on the ground on scaled ICAO reference noise measurement points for three types of maneuvers (Take-off, Landing, Fly over). To complete the investigation, the test matrix schedules different cases with or without the landing gear, various flap configurations as well as different speeds.

Measurement flights oriented towards the assessment of flight dynamics are divided into three topics: maneuvering stability, short period characteristics and changes in the equilibrium due to flap or gear deployment. According to the type of test, the test matrix includes different values for speed, flap configuration and if necessary, bank angle and landing gear status.

The last measurement missions to be prepared have been the ones devoted to the risky evaluation of recovery procedures from Hazardous Flight Conditions. During these experiments, the MFP is set in a critical conditions and a recovery procedure previously validated on a simulator is applied. From an initial set of 16 critical conditions to be analyzed, the test team reduced the range of exploration and focused on the following cases:

- Unsymmetrical deflection of a control surface (elevator, rudder, aileron, flap)
- Elevator blocked in the trim condition
- Unsymmetrical flaps deflection at high speed
- Stall

The test matrix also includes the definition of the trim assessment after an unsymmetrical deflection of both the rudder and aileron.

For all these scheduled tests, the team will decide after each flight on how to proceed, either repeat or go to the next step according to a pre-defined list of criteria. Such a stringent approach maximizes safety during the gradual exploration of the IEP capabilities. Concerning the number of flights, it must be noted that all the described tests will be repeated at least once to improve the accuracy of the analysis for each MFP configuration.

To conclude the flight test preparation, the test team initiated the pilot training based on a 6 degrees of freedom simulator tuned with wind-tunnel data. In parallel, various safety procedures have been specified in order to minimize risk. This list includes in particular:

- Failure cases and associated recovery procedures;
- Rules for parachute use;
- Minimum safety area definition.

5 Next steps

For T14 consortium, a clear objective is to achieve flights to demonstrate the capabilities of the system. But beyond the flight test programme, which was initially planned in the frame of the NACRE project, the team ambition for the next steps is to:

- Improve the test facility with activities regarding the development of a cockpit environment for the GCS and an enhancement of the airframe/avionics characteristics;
- Extend the use of the test facility with the definition of new components to test unconventional configurations and the possibility to use the IEP as a testbed for control laws development.

6 Conclusions

In a first step an analysis revealed the possible scientific and operational gains offered by an Innovative Evaluation Platform and in particular of the scaled model to evaluate new aircraft concept for different aspects. Subsequently, the full design and manufacturing of the system enabled all partners to build a valuable know-how about an unmanned flying platform dedicated to scientific measurements. In addition, specific work regarding acoustics allowed specialists to gather engine noise characteristics to be used in future projects. For all these different reasons, NACRE T14 and the IEP prototype can thus be seen as an important first step in the development of a new test facility based on flights in real atmosphere in Europe. Even if the demonstration of the system capabilities could not be completed, lessons learnt from this project are a great added value and the consortium is strongly committed to continue to work on these bases to have the IEP flying in the near future.

Fig.9. MFP ready for takeoff

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