

Parabolic Flights with Single-Engine Aerobatic Aircraft: Flight Profile and a Computer Simulator for its Optimization

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Received: 30 December 2013 / Accepted: 28 July 2014 / Published online: 12 August 2014
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Abstract We report the results of residual acceleration obtained from initial tests of parabolic flights (more than 100 hours) performed with a small single-engine aerobatic aircraft (CAPI0B), and propose a method that improves these figures. Such aircraft have proved capable of providing researchers with periods of up to 8 seconds of reduced gravity in the cockpit, with a gravity quality in the range of $0.1g_0$, where g_0 is the gravitational acceleration of the Earth. Such parabolas may be of interest to experimenters in the reduced gravity field, when this range of reduced gravity is acceptable for the experiment undertaken. They have also proven to be useful for motivational and educational campaigns. Furthermore, these flights may be of interest to researchers as a test-bed for obtaining a proof-of-concept for subsequent access to parabolic flights with larger aircraft or other microgravity platforms. The limited cost of the operations with these small aircraft allows us to perform them as part of a non-commercial joint venture between the Universitat Politècnica de Catalunya - BarcelonaTech (UPC), the Barcelona cluster BAIE and the Aeroclub Barcelona-Sabadell.

Any improvements in the length and quality of reduced gravity would increase the capabilities of these small aircraft. To that end, we have developed a method based on a simulator for training aerobatic pilots. The simulation is performed with the CAD software for mechanical design Solidworks Motion®, which is widely distributed in indus-

try and in universities. It specifically simulates the parabolic flight manoeuvre for our small aircraft and enables us to improve different aspects of the manoeuvre. The simulator is first validated with experimental data from the test flights. We have conducted an initial intensive period of specific pilot training with the aid of the simulator output. After such initial simulation-aided training, results show that the reduced gravity quality has significantly improved from $0.1g_0$ to $0.05g_0$. We conclude that single-engine aerobatic aircraft are capable of conducting small hypogravity experiments with the limitations described in the paper.

Keywords Parabolic flight · Reduced gravity · Simulation · Aerobatic flight

Introduction

Parabolic flights are a well-known tool for providing researchers and students with reduced gravity opportunities. Space agencies have been providing parabolic flight campaigns for many years by using a variety of aircraft (Pletser 2004). Their main advantages include easy access to reduced gravity; a unique test-bed for technological demonstrations or ready-to-perform experiments, and a lower cost compared to other platforms such as satellites, sounding rockets or the International Space Station. A typical parabolic flight provides up to 25 seconds of reduced gravity, in the range of $10^{-2}g_0$ to $10^{-3}g_0$, depending on the axis measured and other factors such as control of the manoeuvre (Messerschmid and Bertrand 1999). Aircraft such as the Airbus 300 ZeroG from Novespace are also capable of providing Moon and Mars gravities with considerable precision (Pletser et al. 2012). These large aircraft have over the years proven to be very successful in providing a safe,

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reliable and easy-to-access reduced gravity environment for students and researchers. In summary, aircraft provide repetitive periods of reduced gravity by flying a ballistic trajectory preceded and followed by short periods of hypergravity, typically of $2g_0$. In fact, Pletser (2013) has shown that while the trajectory is not strictly speaking a parabola, it is an approximation that is not very far removed from reality.

Some authors have also reported having performed parabolic flights with other types of aircraft. Studer et al. (2010) have successfully conducted a cell culture experiment with a Northrop F-5E “Tiger II” fighter jet. These parabolic flights have shown to provide up to 45 seconds of reduced gravity with $0.05g_0$ residual acceleration. The experiments must be conducted independently and automatically. Gerke and Blum (2009) developed an unmanned air vehicle (UAV) suitable for small parabolic flight experiments. Payloads with a mass of up to 5 kg should also be automatically controlled. They reported parabolas with a duration of up to 12 seconds, with a typical residual $0.1g_0$ acceleration.

We propose the use of a single-engine aerobatic aircraft to perform parabolic flight manoeuvres for research and educational purposes. We have performed test flights for more than 100 hours, thanks to a non-commercial joint venture established in 2009 between the Universitat Politècnica de Catalunya - BarcelonaTech (UPC), the Barcelona Aeronautics cluster BAIE and the Aeroclub Barcelona-Sabadell.

We use a CAP10B single-engine aerobatic aircraft flying out of Sabadell Airport and operating in visual flight conditions (VFR). Weather permitting, a local VFR flight is conducted at less than 20 minutes from the airfield to the area where the manoeuvres are performed. The manoeuvres typically start at an altitude of 1,000m AGL (Altitude above Ground Level), rising up to 1,200m AGL. A typical flight will consist of 10 to 15 parabolas and the total duration of the flight until landing will be approximately one hour. Only one experimenter can fly every time with the pilot, although the flight may be repeated many times during the day, allowing different researchers to fly on board and conduct their experiments. The tests are performed by licensed aerobatic pilots, and the parabolas are manually controlled. A typical parabola will last from 5 to 8 seconds of reduced gravity, with a typical average residual acceleration in the order of $0.1g_0$. The reduced gravity period is preceded by a hypergravity period of up to 4 seconds with up to $3g_0$; followed by another hypergravity period of up to 3 seconds with up to $2.5g_0$.

This particular aircraft is a twin-seater, thus enabling an experimenter to travel on board and conduct the experiments manually, although the aircraft may also carry automated experiments. Small payloads of up to 25 kg with a size of less than 50 cm x 50 cm x 50 cm can be operated by the

experimenter in the aircraft cabin. In addition, the experiments can also be attached to the aircraft structure. In this case, only experiments which are not vibration-sensitive would be suitable. It is also important to mention that experiments involving human subjects can be carried out. This latter possibility has recently been reported by Osborne et al. (2014). In their pilot study for evaluating the effect of mental arithmetic on heart rate responses, these authors have found evidence to suggest that this particular aerobatic aircraft is capable of providing meaningful data for biomedical research under different hypogravity and hypergravity conditions.

Apart from test flights, four research campaigns and two educational student campaigns have since 2009 been performed, based at Sabadell Airport, which is a general aviation airfield located 20km from Barcelona (Spain). A typical research campaign lasts for a full day and consists of up to 6 local flights with an operator and an experiment on board. If weather conditions vary and prevent the aircraft from flying in VFR conditions in the area where the manoeuvres are conducted, then the flight has to be postponed, which imposes a limitation on these operations. However, access to reduced gravity time is short, as the experimenter can reach the flight manoeuvre area in less than 30 minutes from the time he is safely seated in the aircraft before take-off. A JAR (European Joint Aviation Regulations) Class II medical certificate or equivalent, and a flight surgeon consultation briefing are required for the experimenter to be allowed to fly. A safety briefing is conducted before the flight, and technical consultation is provided for the researchers as well as a limited civil insurance provided by the Aeroclub Barcelona-Sabadell. A student campaign consists of between 2 and 6 local flights, where the student conducts his or her experiment on board during every flight. A team of 2 to 6 students can therefore conduct their experiments over the course of a single day. These educational campaigns are known as the “Barcelona Zero-G Challenge”, an international contest organized by the authors of this paper and aimed at motivating students to conduct research in this area. For example, the first three authors in Osborne et al. (2014) were the winners of the 2011 Barcelona Zero-G Challenge edition. Their proposal, mentored by Dr. Nandu Goswami and subject to a peer-review process conducted by European Low-Gravity Research Association (ELGRA) senior researchers, was selected as the best one submitted to the contest, and later flown from Sabadell Airport (Barcelona, Spain).

As the in-flight operation is totally manual, the pilots skill is critical for optimizing the reduced gravity quality and the reduced gravity time achieved. A real-time training system would be desirable to train the pilot in order to improve the quality of these manoeuvres. In this paper, we propose an original development of a specific parabolic

manoeuvre computer simulation for these particular aircraft. The simulator is developed by using a state-of-the-art standard software framework such as Solidworks Motion® (Dassault Systèmes SolidWorks Corp 2013). The objective of this simulator is to optimize the time and the quality of the reduced gravity manoeuvre. This simulator allows us first to reproduce the operations performed by the pilot, and later to propose new flight profiles. The new profiles can be tested again during the flights, thereby providing a flowchart of operations aimed at improving the overall quality of the flight.

The simulator is based on a parametric model of the air-plane and can also be applied to other models of small single-engine aircraft, thus providing new insights into the parabolic flight manoeuvre in different configurations. The software may also be a useful tool for improving the training procedures of aerobatic sport competitors.

This paper presents the flight fundamentals of the manoeuvre, and how the numerical simulation reproduces the forces involved. Results of the simulation for the CAP10B plane are shown with optimized profile flight proposals. Experimental results from a typical parabola measured during the flight are used to validate these simulations. A discussion on the simulation output follows. Finally, results are given for an initial intensive simulation-aided training period, where a significant improvement of the reduced gravity quality is found.

Flight Simulation

Flight simulators were introduced historically for training and for pilot certification. These systems may incorporate several components to a greater or lesser extent: Computer Hardware, Flight Instruments (Avionics), Software and Mathematical Models, Motion Systems with various degrees of freedom of movement and hydraulic systems incorporating Computer Generated Imagery (CGI).

By the mid-1970s two alternative flight simulation approaches had emerged (Rosenkopf and Tushman 1998):

- *Full flight simulators* (FFSs) costing \$15 to \$20 million dollars faithfully replicating the flight experience by integrating cockpit instrumentation with full motion and the possibility of visually simulating the flight.
- *Flight training devices* (FTDs) costing \$1 to \$3 million dollars and having no motion or visual capabilities. This type of device is used to train a pilot in certain skills.

These simulators have proprietary equations and flight test data that integrators must buy from aircraft manufacturers.

The quality of the reduced gravity attained is expected to improve with manual training. A real-time visual help

to assist the pilot in executing the manoeuvre precisely is expected to be useful for this training. Our challenge is to provide useful flight instructions to help the pilot to follow an optimal parabolic flight trajectory. To this end, neither FFS nor FTD type simulators are suitable; rather we propose a motion-simulation software designed for mechanical applications. Motion simulation provides quantitative information about the kinematics (position, velocity and acceleration) and the dynamics (joint reactions, inertial forces and power requirements) of the components of a moving mechanism. This analytical approach is very common in the general field of engineering mechanics.

Accordingly, we propose the performance of simulations using a parabolic flight simulator at an affordable cost, based on the CAD Solid works Motion® (Dassault Systèmes SolidWorks Corp 2013) software for mechanical design, which is widely distributed in industry and in academic environments.

Solid Works Motion® is a virtual prototyping tool for engineers and designers powered by ADAMS® technology. More precisely, it allows the study of the motion of a system or mechanism determined by:

- Mates connecting the parts (limiting Degree Of Freedom (DOF) between parts).
- The mass and inertia properties of the components.
- Applied forces to the system.
- Driving motions (Motors or Actuators).
- Time.

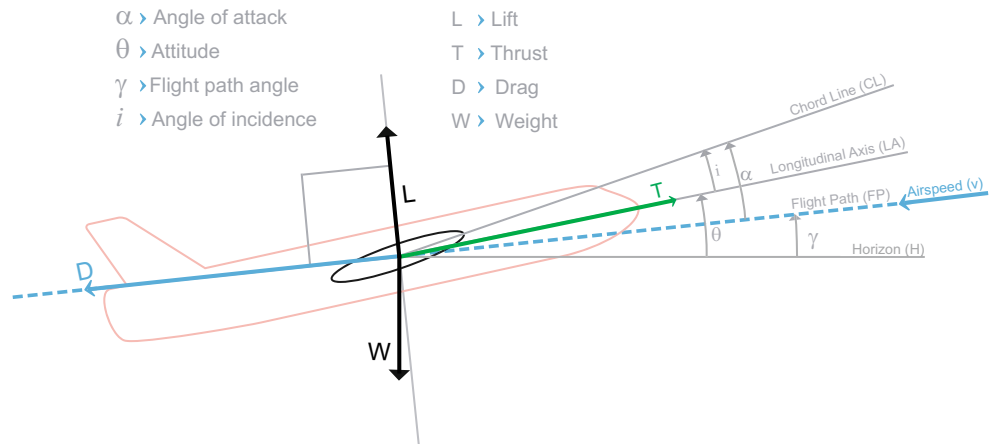
Solid Works Motion® allows the animated simulation to be viewed and presents the results as graphs and tables of data showing the forces, speeds, displacements and accelerations to which the parts of the simulated mechanical system are subjected.

Modelling the CAP10B for Parabolic Flight

The analysis based on a flight simulator enables the process to be approached in terms of flight parameters; if a stable atmosphere is assumed, with zero wind speed, then Airspeed equals Ground Speed. Air density is regarded as constant, since the simulation of the parabolic flight is conducted at an altitude difference of 550 feet (between 3,300 feet and 3,850 feet in standard atmosphere), which yields a variation of 1.6 % in Air Density and Lift, which is negligible for the results of this simulation (see Fig. 1):

- Weight, W
- Air Density, ρ (assumed to be constant in this simulation)
- Lift, L
- Thrust, T

Fig. 1 Simulation elements



- Air resistance (Drag, D)
- Angle of Attack (Attack, α)
- Angle of Attitude (Attitude, θ)
- Angle of Incidence (Incidence, i)
- Relative air speed (Airspeed, v)
- Measurement of the relative gravity in the cabin (Relative Gravity, RG)

The parameterization of these variables and their extrapolation are made with data extracted from the APEX Aircraft CAP10B flight manual (2003).

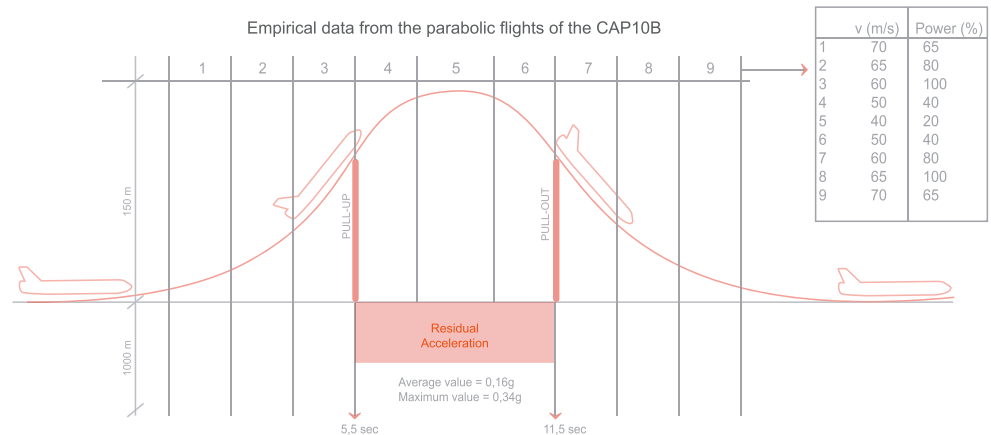
The model parameters are checked and adjusted with the empirical data from the initial CAP10B parabolic test flights. Several simulations are performed, adjusting and assessing the impact of each variable. We use the data obtained from modelling the airplane, combined with the original experimental data provided directly by the pilot (see Fig. 2). This figure shows the data concerning Altitude, Speed and Power obtained experimentally during the parabola of these test flights.

Experimental profiles of parabolic manoeuvres

A typical manoeuvre consists of an initial pull-up phase, from horizontal flight at a level of 1,000 meters AGL, where the nose of the aircraft is lifted to about 42 degrees, and full thrust is applied. The power of the engine is then reduced to the minimum required to compensate air drag. After that, the aircraft follows the trajectory of a parabola, and during this parabola the attitude of the aircraft varies until a maximum negative tilt angle is reached at the end of the reduced gravity time. Then, the pull-out phase follows, causing a second peak of hypergravity inside the aircraft. This phase ends when the aircraft’s attitude is stabilized again and horizontal flight is resumed. The maximum altitude reached is typically less than 1,200 meters from the ground.

Below, one may observe (Fig. 3) a typical example of residual acceleration values recorded on an accelerometer in one of the first test flights with the CAP10B light aircraft. Maximum errors for the accelerometer are less

Fig. 2 Empirical data from the CAP10B parabolic test flights



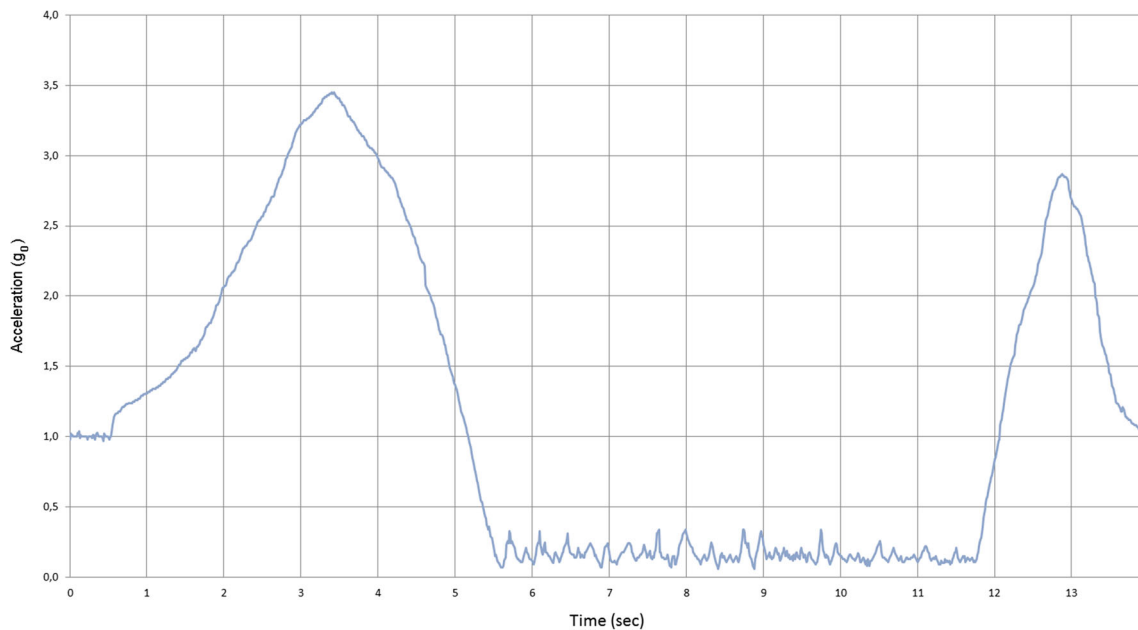


Fig. 3 Empirical data of acceleration from the CAP10B parabolic flights. Example of typical values of acceleration obtained after just 5 hours of training

than $10^{-3}g_0$. The maximum residual acceleration obtained during the reduced gravity time is $0.34g_0$, minimum value is $0.06g_0$, mean $0.16g_0$, and standard deviation 0.05 for a total of 6 seconds. Average Residual acceleration in the order of $0.1g_0$ are therefore easily obtained with this aircraft (see Fig. 3).

Between 2008 and 2010, flight tests were conducted by the aerobatic pilots of the Aeroclub Barcelona-Sabadell, the second largest in Europe in flight hours flown per year. These flight tests consisted in a manual repetition of the parabolic manoeuvre with the CAP10B in a local area over the vicinity of Sabadell Airport, in VFR conditions and always in wind speeds of less than 15 knots. This small aircraft has been reported to be sensitive to wind gusts, so these conditions should be avoided during the parabolas. The CAP10B was configured with no additional loading and with a single pilot on board. Some flight tests were conducted with another aerobatic pilot on board, but the pilot-in-command always remained in complete control of the manoeuvre. After 100 hours of test flights, some improvements were achieved in the flight profile. A typical parabola performed after this initial specific training can be seen in Fig. 4.

The reduced gravity time was increased from 4–6 seconds to an average of 7–8 seconds, which is a significant improvement of more than 1.8 times of the initial reduced gravity time achieved with no specific training. It is also important to mention that the hypergravity peaks in the pull-up and pull-out phases were significantly reduced. The initial acceleration peak was reduced to less than $3g_0$, and the

final peak to less than $2.5g_0$. These improvements are significant, since they enable the manoeuvre to be made more smoothly, and thus the researcher on board experiences less acceleration loads during the flight. However, the residual acceleration, measured with an accelerometer, whose maximum error is $10^{-3}g_0$, remained in the same order of $10^{-1}g_0$, with a slight improvement, which has no significance (maximum $0.34g_0$, minimum $0.04g_0$, mean $0.12g_0$ and standard deviation 0.03).

It was not clear whether a longer training time, but without adequate feedback for the aerobatic pilot executing the manoeuvre, would lead to better results with respect to the quality of reduced gravity. Given that other types of aircraft mentioned in the introduction obtain residual accelerations that are below at least $0.05g_0$, we should address how to improve this technique, taking into account that we lack any specific references for this particular type of single-engine light aircraft. This leads us to consider the need to develop a specific method to provide the pilot with definite references during flight time and the execution of the manoeuvre. To that end, we have developed the simulator described in the following section. This first involves the validation, with experimental data taken from the test flights, of a simulation in motion of the parabola, and subsequently providing specific data on the Attitude (θ) and the Power of the engine (P) required in real time during the parabola. Such data would enable simulation-aided training to be undertaken, and has finally shown to significantly improve the residual acceleration values obtained with this particular aircraft.

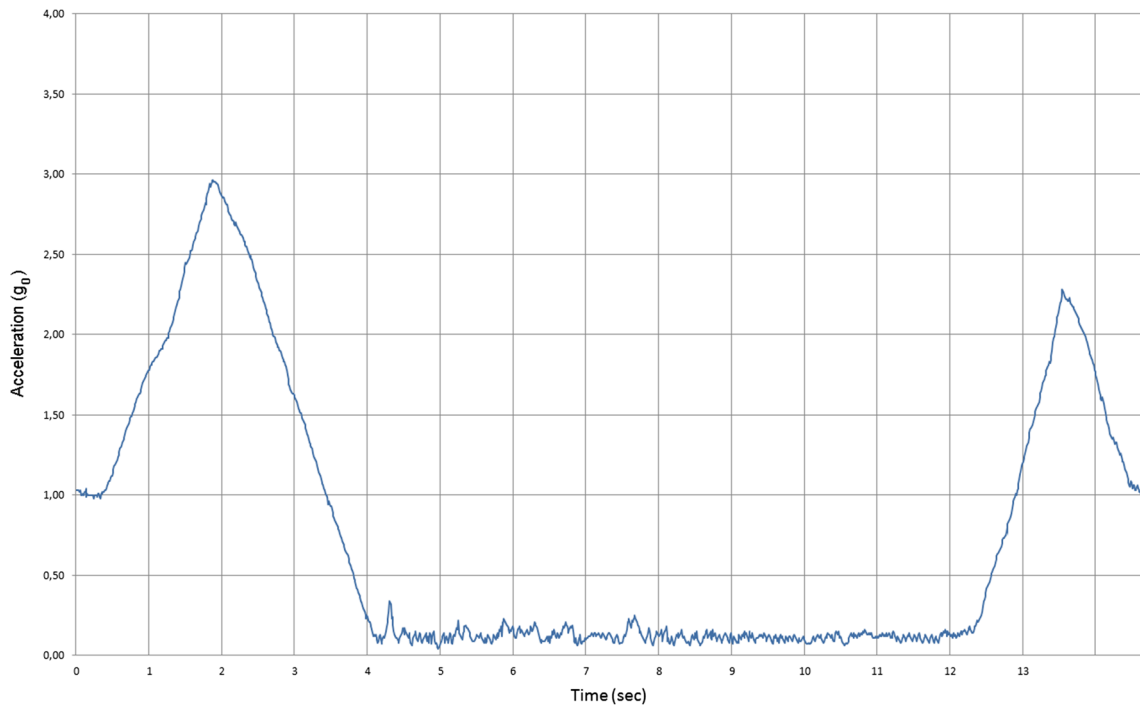


Fig. 4 Empirical data of acceleration from the CAP10B parabolic flights. Example of typical values of acceleration obtained after more than 100 hours of specific training

Description of the Simulator

The project has two parts: a 3D model and the motion simulator. The 3D model consists of 4 rigid elements:

1. Aircraft, with physical CAP10B model parameters.
2. Content, simply a ball of known mass located by a mate relationship at the aircraft’s center of mass. It is possible to measure the forces to which it is subjected and thus determine the relative acceleration of the airplane contents.
3. Dir-Control(1). This part is attached to the airplane by a hinge connection that enables motion in the airplane profile plane. Its position follows the wind direction

(Relative wind) and its calculation is based on the Airspeed. This part enables the direction of the Lift force to be changed.

4. Dir-Control(2). This part is also attached to the airplane by a hinge connection that enables motion in the airplane profile plane. Its position is allocated by a table and is one of the aircraft piloting parameters (Angle of Attack, α). Its position is used to calculate the magnitude of the Lift force and is interpolated throughout the entire simulation.

The Motion Simulator model consists of the following active components:

1. Gravity (9.81 m/s^2)

Start X	End X	Value	Segment Type
-	-	2000.00N	Initial
0s	1s	2500.00N	Cubic (Defa
1s	2.5s	2500.00N	Cubic (Defa
2.5s	2.8s	2100.00N	Cubic (Defa
2.8s	3s	2014.00N	Linear (Def
3s	5s	1262.00N	Linear (Def
5s	7s	974.00N	Linear (Def
7s	9s	1090.00N	Linear (Def
9s	11s	1628.00N	Linear (Def
11s	13s	2700.00N	Linear (Def
13s	14s	2700.00N	Cubic (Defa
14s	15s	2000.00N	Cubic (Defa

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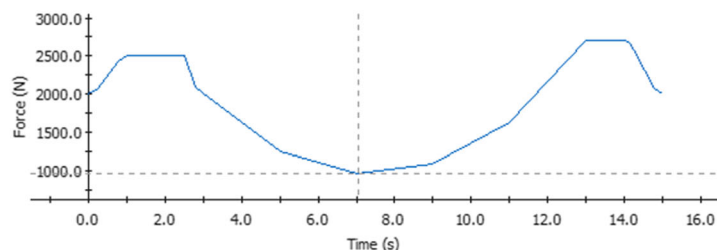


Fig. 5 Profile of the applied Thrust

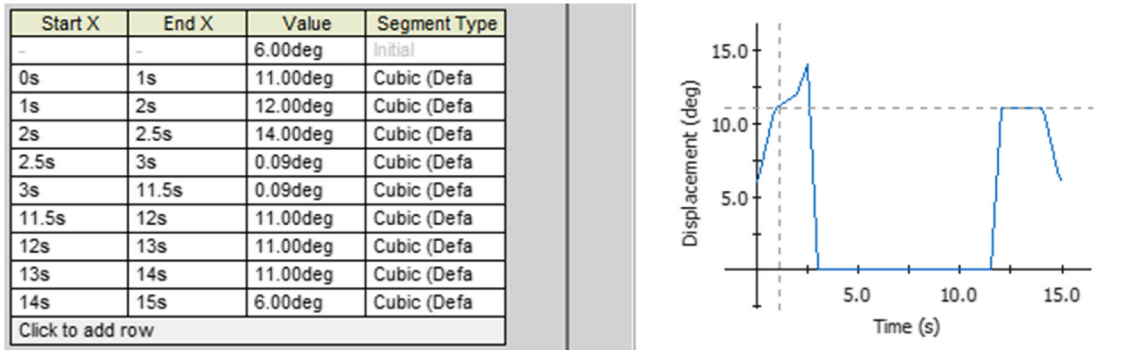


Fig. 6 Profile of the applied Attack angle

2. Lift force:

$$L = \alpha * v^2 * K_{L-CAP10B}$$

where:

α = Angle of Attack (assumed to affect the lift directly)

v = Airspeed, in the simulation it is equal and opposite to the velocity of the airplane

$K_{L-CAP10B}$ = Aircraft constant obtained empirically (contains the air density value, ρ , which is assumed to be constant during the parabola).

3. Thrust, which simulates the action of the pilot (see Fig. 5):

$$P = T * v * K_{P-CAP10B}$$

where:

T = Thrust

v = Airspeed

$K_{P-CAP10B}$ = Aircraft constant obtained empirically.

4. Wind, positions the wind element:

$$\beta = \arcsin\left(\frac{v_y}{v}\right)$$

where:

v_y = Vertical component of the Airspeed

v = Airspeed.

5. Attitude (θ), forces the Aircraft Attitude; it simulates the action of the pilot:

$$\theta = \gamma + \alpha - i$$

where:

γ = Flight path angle

α = Angle of Attack

Fig. 7 Forces compensation during the reduced gravity time

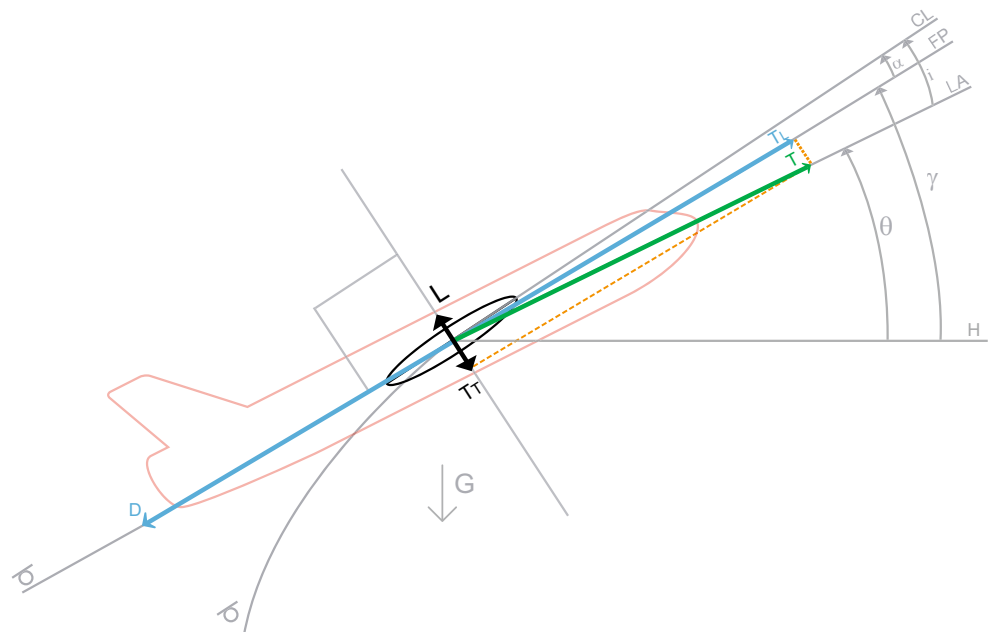


Table 1 Values obtained during the reduced gravity period

	Empirical data	Optimized simulation
Reduced g time (sec)	8	8.5
Maximum g (g_0)	0.34	0.007
Average g (g_0)	0.12	0.003

i = Angle of Incidence, fixed value of each airplane model.

- Attack, positions the attached element used to obtain the Angle of Attack, α , in the formula of the Lift (L). It simulates the action of the pilot (see Fig. 6).
- Drag force, Parasitic Drag, (the Induced Drag is neglected because the angle of attack is virtually zero in the reduced gravity period, which gives rise to an almost zero Lift).

$$D = v^2 * K_{R-CAP10B}$$

where:

v = Airspeed

$K_{R-CAP10B}$ = Aircraft constant obtained empirically (contains the air density value, ρ , which is assumed to be constant during the parabola).

Optimization Method

In order to obtain zero gravity in an environment, gravitational forces should be the only ones that affect all the elements of the environment equally. Nevertheless, when an aircraft moves through the air Drag (D) and Lift (L) forces are produced, and thus zero gravity implies either eliminating them or counteracting their effect. The process is analyzed only in the Reduced Gravity period of the parabola after pull-up and prior to pull-out. In this period one observes that Drag can be compensated for by means of

a Longitudinal Thrust (T_L , Fig. 7) of equal magnitude, since both are tangent to the curve of the Trajectory.

It should be possible to eliminate the Lift by adjusting the Angle of Attack to a value close to zero, although a certain value of Lift should be maintained, which enables a small component of the Thrust perpendicular to the Trajectory (T_T) to be compensated for. Given that the Drag has been modeled in the simulator, it is possible to apply the right amount of power to obtain a Longitudinal Thrust of equal value. It is also possible to adjust the Attitude in the simulator to obtain the Angle of Attack that enables compensation of the Transverse Thrust (T_T). In the initial tests, the constants $K_{L-CAP10B}$ and $K_{D-CAP10B}$ for the aircraft are adjusted in the simulator so that results similar to those provided by the pilots own experience and monitoring with an accelerometer are obtained (see Fig. 4). Values of air resistance at each point of the trajectory are also obtained; these values are used in the optimized method to define the profile of the applied power.

Simulator and In-flight Experimental Results with the Optimized Method

In the optimized case, balance forces are achieved thanks to prior knowledge of the air resistance, so the quality of the Reduced Gravity can be improved. The values obtained of residual acceleration are shown in Table 1.

These values correspond to the exact profile of the simulator output, which is depicted in Fig. 8.

The average of relative gravity in the reduced gravity period (3 secs to 11.5 secs in Fig. 8) is $3.10^{-3}g_0$, which is a value 40 times less than that obtained on real flights. This simulator value constitutes a significant improvement. In order to simulate the pilot's ability to manoeuvre, the Power and Attitude instructions are provided in real time by using a visual display in the cockpit. Power and Attitude figures for the optimized case are depicted in Figs. 9 and 10, respectively.

Fig. 8 Simulation of acceleration in the optimized case

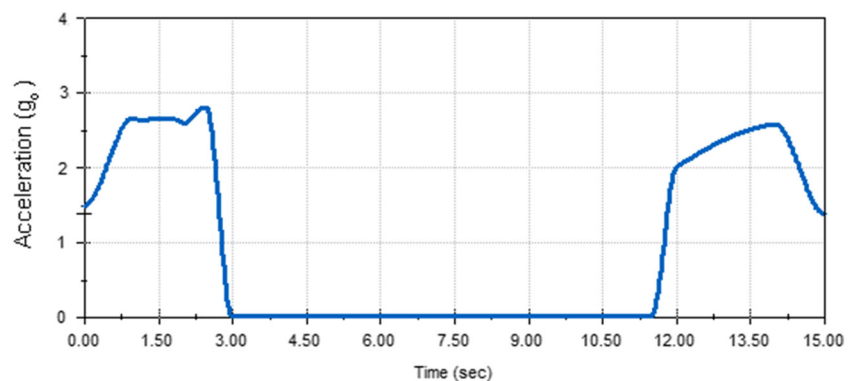


Fig. 9 Applied power (*output from the simulator*) in the optimized case

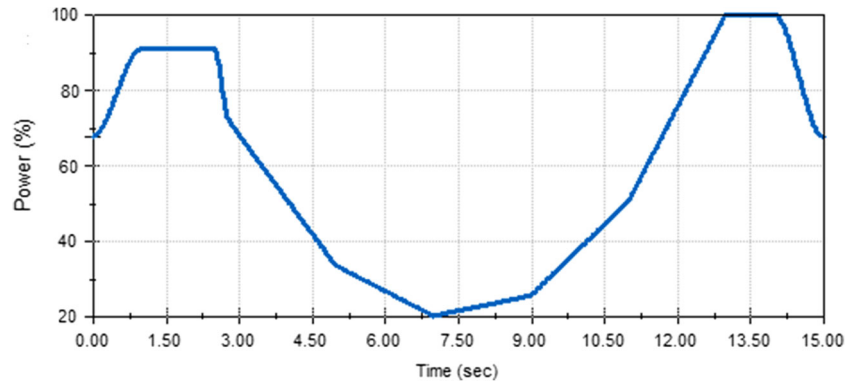


Fig. 10 Attitude angle (*output from the simulator*) in the optimized case

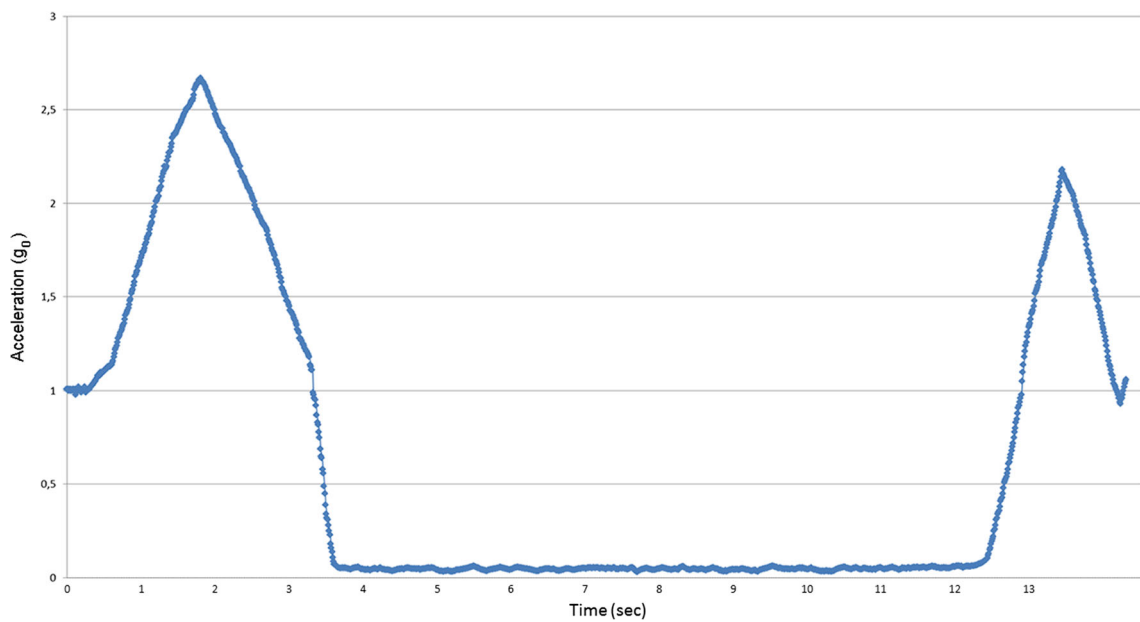
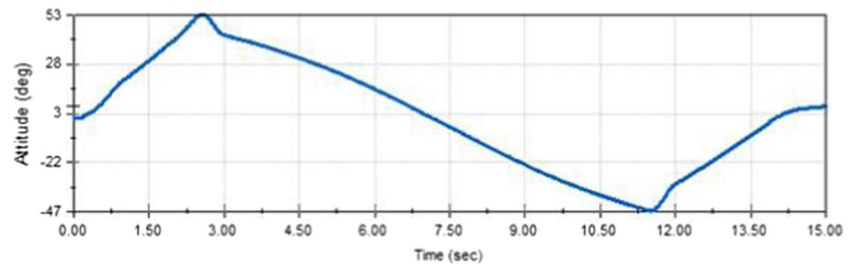


Fig. 11 Empirical data of acceleration from the CAP10B parabolic flights after simulator-aided specific training. Example of typical values of acceleration obtained

The applied power has a very similar profile when compared to the curve of the Thrust (see Fig. 5), since the velocity values are comparatively small:

$$P = T * v * K_{P-CAP10B}$$

Finally, we show the Attitude Values obtained with the simulator, which are displayed to the pilot, as well as for the optimized case (see Fig. 10).

These results from the simulator, validated according to the experimental profile data, encouraged us to continue this work and provide pilots with a display for better training. We report in-flight experimental results after an intensive specific period of training of 30 hours. This period of training included briefings were specific instructions that were given to the pilot to perform the manoeuvres, in-flight training with a display in the cabin showing real time simulator output results, and debriefings. A typical parabola obtained after this initial period of simulation-aided specific pilot training is shown in Fig. 11.

The maximum residual acceleration obtained during the reduced gravity time is $0.065g_0$, minimum value is $0.031g_0$, mean $0.047g_0$, and standard deviation 0.006 for a total of 8.6 seconds. Average residual acceleration has significantly been reduced from the order of $0.1g_0$ to approximately $0.05g_0$ after just 30 hours of intensive simulation-aided training. The initial acceleration peak has been reduced to $2.67g_0$ and the final acceleration peak has also been reduced, up to $2.18g_0$. Total reduced gravity time (8.6 seconds) is slightly longer than those initially obtained (about 8 seconds), and it is compatible with the value obtained with the simulator (8.5 seconds).

Discussion, Conclusions and Future Work

A series of flight tests have been conducted to evaluate the capabilities of single-engine aircraft like the CAP10B model for reduced gravity research. The results presented in this paper show that these aircraft provide an environment of reduced gravity for small experiments with a gravity quality in the order of $0.05g_0$ for as long as 8.5 seconds. The time and flight profiles are achieved by licensed aerobatic pilots with 100 hours of specific training, followed by an intensive period of at least 30 hours of simulation-aided specific training. This platform fulfills some of the requirements of parabolic flights (easy access to the platform; limited cost of operations, and a test-bed for technological demonstrations or ready-to-perform experiments). The experiments can be run as fully automated or operated by an experimenter on board. However, these small aircraft exhibit some limitations, such as being dependant on VFR weather flying conditions, size and weight constraints due to limited cabin space, able to carry only one or two experiments

at a time, and significant sensitivity to wind gusts. The gravity quality finally achieved is therefore, approximately $0.05g_0$.

The hypergravity peaks at the transitions, prior to and after the reduced gravity time, are significantly higher and more acute than those experienced in larger aircraft. However, for a healthy crew member who has passed a standard EASA Class II aeronautical medical certification or equivalent, flying should not be a problem. Four research and two educational campaigns have so far been conducted, with 16 different participants (different from the aerobatic pilots) present on parabolic flights in the CAP10B (13 men, 3 women), and no medical issues or motion sickness having been reported. All participants passed a medical check conducted by a certified flight surgeon before take-off. No accidents or operational incidents during these flights have been reported to date.

In order to overcome the residual accelerations of these parabolic flights, we have proposed a method to improve the initial figures obtained for this particular CAP10B aircraft model. The method consists of using a real-time display in the cockpit of the aircraft to give constant references to the pilot while performing the manoeuvre. The results of this display come from a simulator developed with a Generic Motion-Simulator for Mechanical Engineering - SolidWorks Motion®. This software has led to the development of a simulator for the parabolic manoeuvres performed by this particular type of aircraft. The optimized simulation is a theoretical study by means of which the width between the highest peaks of residual acceleration has been reduced by 50 times in the period of Reduced Gravity, and the mean value 40 times, while in the phase of Reduced Gravity the time has been increased by 6%, always when compared against the empirical data of residual acceleration coming from the initial CAP10B test flights. The method has been experimentally tested with an intensive specific period of training of 30 hours of flight. It may be argued that these additional training hours have an incremental effect on the quality of the parabola performed. However, it is significant that, after the initial period of 100 hours of training no significant improvements were found in the residual acceleration obtained, but then after only 30 additional hours of simulation-aided training these figures improved from the order of $0.1g_0$ to approximately $0.05g_0$. The total reduced gravity time was not particularly increased, and remained in figures compatible with the simulator output. As total reduced gravity time is mainly dependant on the engine power of the aircraft, this result was something that could be expected.

In order to increase the total reduced gravity time, we plan to perform parabolic manoeuvres with aerobatic aircraft which are equipped with more powerful engines such as the EXTRA100 model. It is expected that longer reduced

gravity times of up to 10 or 12 seconds could be achieved with more powerful engines. Also, we plan to perform more flight tests in future, adding more flight hours to the specific training of the aerobatic pilots. However, and given the limitations of manual piloting of these small aircraft, it is doubtful that the reduced gravity quality can be significantly increased far below $0.05g_0$. We also plan to model wind gusts on this particular aircraft, and classify their effects on the residual acceleration obtained. In future, that may give hints to optimize the manual operation of the aircraft when wind gusts appear during the parabola.

Therefore, we conclude that this experimental platform can be suitable for reduced gravity small experiments when the range of $0.05g_0$ reduced gravity quality is acceptable. Also, it has proven to be successful and capable to provide meaningful data for educational campaigns or for physiological experiments on humans where different loading conditions are needed (Osborne et al. 2014). The platform can certainly be a good testbed for a proof-of-concept before accessing other platforms which provide significantly better reduced gravity quality such as larger aircraft, sounding rockets or other microgravity platforms.

Acknowledgements Thanks are due to Dr. Nandu Goswami for his interesting comments and suggestions. We are particularly grateful to the pilots of the Aerobatic Team of Aeroclub Barcelona-Sabadell, who with their skills and dedication made these operations possible. We are also grateful to the following institutions that support this research: Universitat Politècnica de Catalunya - BarcelonaTech (UPC), the Barcelona cluster BAIE and the Aeroclub Barcelona-Sabadell. The authors would also like to acknowledge the anonymous reviewers who

with their constructive comments have improved the quality of the manuscript.

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