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The interactive physics flight simulator

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Summary. — This paper describes a modelling approach to the dynamics of the airplane flight aimed at designing and realizing a simple but realistic "flight simulator", able to mimic the longitudinal behaviour of a real airplane. The model is implemented by using the Interactive Physics simulation environment. The simulator is used to reproduce all the phases of a complete flight of a light commercial airplane. All the actions on plane controls are analyzed and explained in terms of equilibrium states of the system. The main objective of the obtained simulations is in making the physical phenomenon understandable to students with a basic knowledge of mechanics and not involved in specialized aerodynamics studies.

PACS 01.50.-i – Educational aids.
PACS 01.50.F- – Audio and visual aids.

1. – Introduction

Teaching and learning physics via a flight simulator is an example of a pedagogical strategy in which physics contents are framed in the context of a familiar and fascinating experience.

Even if many simulators are available and most of them are very realistic and with amazing graphics, very few allows to explore the physics models inside them.

Moreover, physics of aircraft pilotage involves different content fields (dynamics, electromagnetism, thermodynamics etc.) and at the same time offer a chance for engaging students in modelling approach to a real world phenomenon and for proposing some pedagogical strategies, dealing with real-world systems and everyday problem solution, which can contribute to avoid disaffection in scientific subjects, as the physical ones, making them more attractive.

The argument of this paper deals with an ICT-based modelling approach to examine the dynamics of airplane longitudinal flight and to develop a pedagogical flight simulator which can be used to improve the understanding of physics of flight and of some advanced mechanics contents.

From a pedagogical point of view, we think that this kind of tool might be used to build up several activity-based proposals aimed to make students aware of the reasoning procedures to describe, formalise and explain the behaviour of some real systems as the airplanes.

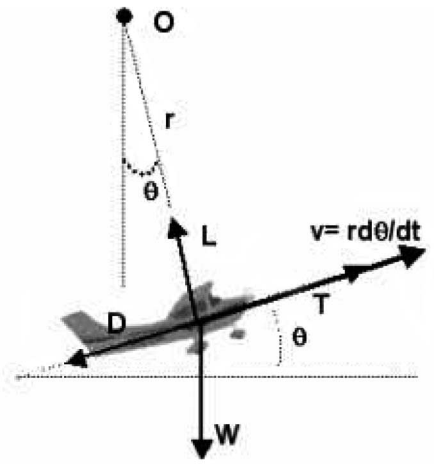

Fig. 1. – Radial and tangential forces with respect to the intantaneous centre of rotation O.

2. – The physics model for longitudinal airplane flight

Consider the airplane a point mass subjected to the four forces (thrust T, lift L, drag D and weight W) regulating the longitudinal flight. The motion equations of the system will be simpler by writing them in terms of the radial and tangential components of the net force with respect to an instantaneous centre of rotation O (fig. 1) (Anderson, 2005).

As experiments in the wind tunnel show that lift and drag are proportional to the squared speed, we can write

$$\begin{aligned} T - k_D v^2 - W \sin\theta &= m\frac{\mathrm{d}v}{\mathrm{d}t}, \\ k_L v^2 - W\cos\theta &= m\frac{v^2}{r}, \end{aligned} \tag{1}$$

where v and θ are the speed and the pitch attitude of the plane respectively, while k_L and k_D are two parameters depending on the aircraft geometry (wings shape, surface etc.), on the angle of attack and on the air density. The distance r between the centre O and the centre of mass of the airplane can be eliminated by taking into account the relation $v = r\mathrm{d}\theta/\mathrm{d}t$. By doing this, eqs. (1) will become

$$\begin{aligned} T - k_D v^2 - W \sin\theta &= m\frac{\mathrm{d}v}{\mathrm{d}t}, \\ k_L v - \frac{W\cos\theta}{v} &= m\frac{\mathrm{d}\theta}{\mathrm{d}t}. \end{aligned} \tag{2}$$

The system of equations (2) is a non-linear first order differential equations and cannot be solved exactly. The analysis of steady-state solutions can be easily carried out and is found elsewhere (G. Tarantino *et al.*, 2008).

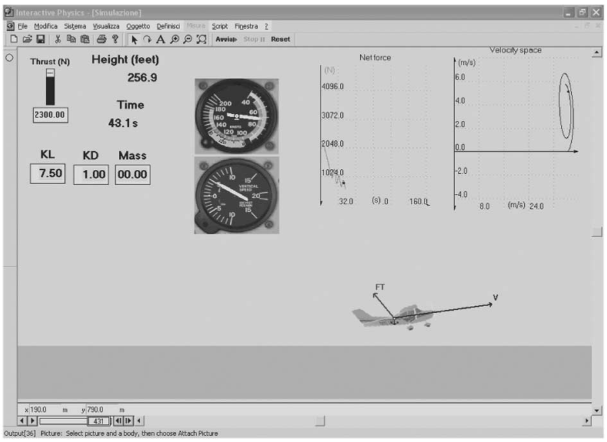

Fig. 2. – A screenshot of the flight simulator showing a frame just after the take-off.

3. – The flight simulator

In order to perform the numerical integration of (2), we have implemented a flight simulator able to visualise the time dependence of the relevant kinematics variables and allowing the parameters of the model to be changed during simulation. A screen-shot of this simulator built up with Interactive Physics is reported in fig. 2.

The three relevant parameters represented by lift and drag coefficients and thrust may be associated to the aircraft longitudinal controls. In this way, the main actions performed during flight by pilots for manoeuvring the aircraft can be simulated by setting and changing these parameters opportunely. We can easily reproduce the action on the throttle by changing the thrust value from 0 to $T_{\max}$ and the action of flaps extension by changing the lift and drag coefficients. Flaps are, in fact, moveable surfaces situated on the rear edge of wings causing the increasing of aerodynamical efficiency used to reduce the take-off and landing speeds. We will analyse the behaviour of a light commercial propeller aircraft (mass = 1300 kg and maximum thrust = 2.5 kN) whose features are summarized in table I.

Here we report the results of the flight simulation obtained by applying a traditional Runge-Kutta 4 integration method. The flight has been divided into five different phases:

1) *Take off* - Plane initially at rest on the runway with flaps in take-off configuration and throttle set to the maximum value of 2.5 kN.

2) *Climb* - Throttle maintained to its maximum value during all the climb, but flaps have been retracted.

3) *Cruise* - When the plane has reached an height of 1000 ft, thrust is reduced to

Table I. – *Values of airplane parameters.*

Mass (kg)	Thrust (kN)	k_D (kg/m)	k_L (kg/m)	Efficiency (k_L/k_D)
1300	0–2.5	1	9	9 (without flaps or “clean” configuration)
		1.05	10	9.52 (Flaps in take-off configuration)
		1.1	12	10.9 (Flaps in landing configuration)

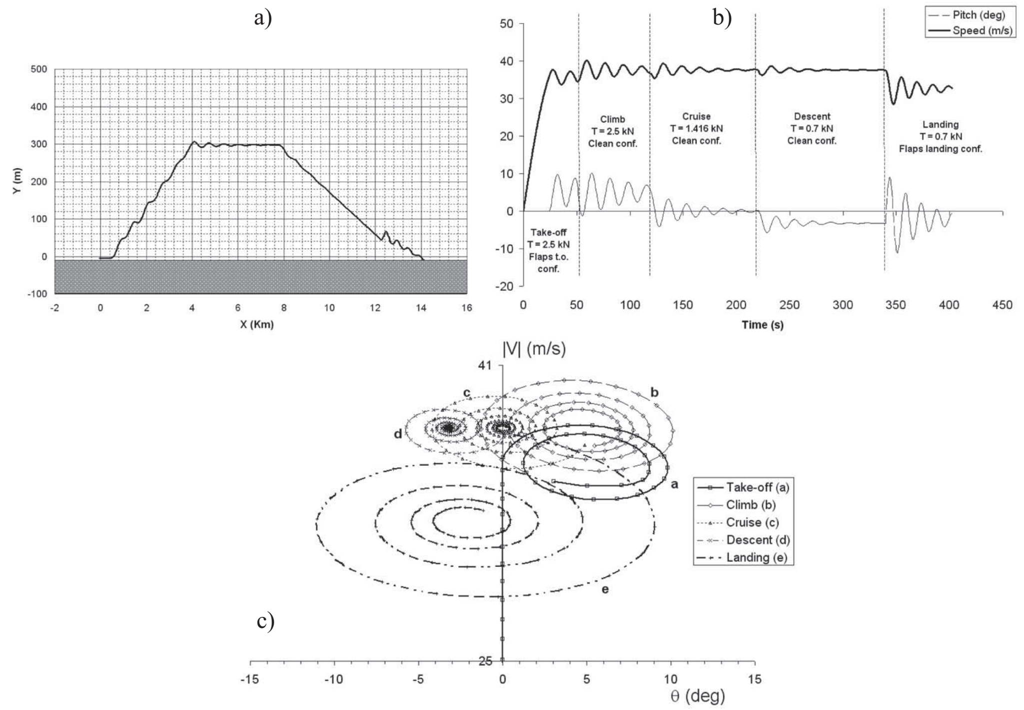

Fig. 3. – (a) Trajectory drawn by the plane (b) Plot of speed (black curve) and pitch (light curve) *vs.* time. Both variables perform damped oscillations around equilibrium values. The five phases of the flight are well distinguishable. (c) Representation of the simulation in phase space (v, θ). We can easily recognize five spirals wrapping around five different centers.

1.416 kN (this is the thrust for horizontal flight given by condition $W = L$).

4) *Descent* - Throttle is reduced to 0.7 kN.

5) *Landing* - Flaps are extended to assume landing configuration and thrust is left unchanged.

Note that, in setting phases 3 and 4, we have applied one of the most important tips contained in all the pilotage hand-books according to which climbs and descents must be set acting on throttle instead of pulling or pushing the control yoke as one could think([1]).

We have observed the flight path during the various phases of the flight and measured the relevant kinematics variables (speed, vertical velocity, pitch, altitude etc.) usually monitored by the basic instruments situated in a standard panel of a real cockpit.

The analysis of flight path (fig. 3a) and of time evolution of speed and pitch (fig. 3b) has shown a relevant result: the response of the system to a perturbation represented by variations of thrust and/or efficiency is always a damped long-period oscillation around

([1]) See, for example, the Microsoft Flight Simulator 2004 Tutorial about climbing and descending: "At this stage of your training, it's a good time to agree on how you'll control the airplane. Power (throttle position) should be your means of adjusting the rate of descent. The airplane's pitch attitude (controlled by the joystick) is your means of maintaining a specific airspeed. In a climb, you'll always use the maximum allowable power (usually full throttle) while adjusting the airplane's attitude using the joystick for the airspeed desired".

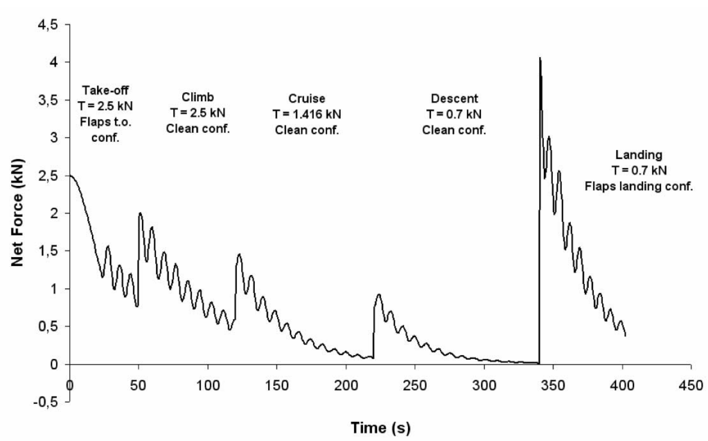

Fig. 4. – Plot of modulus of net force acting on the plane *vs.* time.

equilibrium configurations corresponding to a particular setting of physical parameters of frequency f_0 characteristic of the system (in this case $f_0 = 0.06\,\mathrm{Hz}$).

This damped-oscillating behaviour is made clearer by the representation of flight in the bi-dimensional phase space (v, θ) (fig. 3c). This space may be subdivided in three main regions: θ-positive, θ-zero (v-axis) and θ-negative region in which we can find respectively all the dynamical states corresponding to climbing, horizontal flight and descending. By looking at building up of the phase space trajectories during evolution of flight, one can see spiral-like trajectories as wrapping around steady-state points represented by the spiral centre. When a perturbation on the system is introduced by thrust and/or efficiency variation, a transition to a different spiral is induced. In detail, one can see that take off is represented by the vertical straight line coinciding with v-axis. When take-off speed (35.7 m/s) has been reached, the trajectory moves into θ-positive half-space (spiral a). Retraction of flaps induces the transition to spiral b centred on a higher value of speed and lower value of pitch. When thrust is reduced to its horizontal value, transition to spiral c centred on v-axis ($\theta = 0$) occurs. Further reduction of thrust induces transition to spiral d centred into θ-negative half-space and finally flaps extension before landing allows achievement of an equilibrium configuration characterised by lower speed and pitch. We can summarize these results by stating that increasing of efficiency induces transitions to higher pitch and lower speed. On the other hand, increasing of thrust causes transitions to higher pitch leaving speed approximately unchanged.

It is also very interesting to consider the time evolution of tangential and radial components of the net force acting on the aircraft. We find that both components perform damped oscillations around zero with frequency f_0. Composition of the two forces gives raise to a vector rotating with the characteristic frequency f_0 of the system whose modulus decreases exponentially to zero with a modulating frequency $f = 2f_0$ (fig. 4). Variations of parameters induce steep variations of net force.

These long-period oscillations we found are well-known in aerodynamics. The corresponding motion is named "phugoid motion" (Lancester, 1910). This is one of the

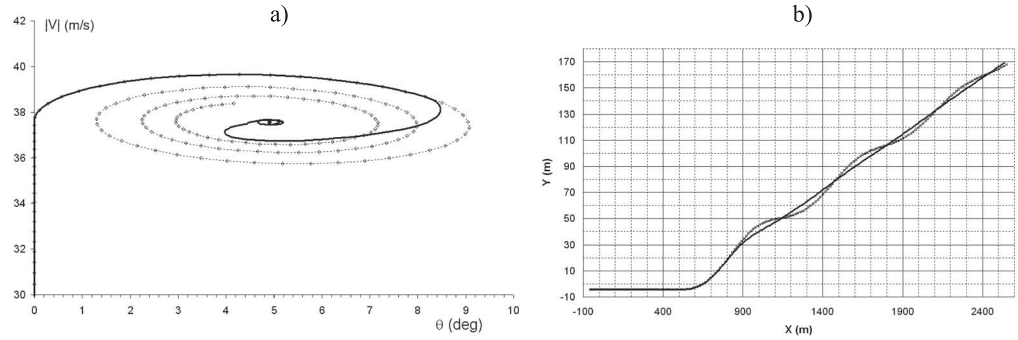

Fig. 5. – The action of trim in the phase space (a) and on the real trajectory (b). In both cases we have plotted trajectories of the flight in the same conditions but without trim (light curves).

airplane characteristics tested by pilots for dynamical stability([2]). It is established by perturbing the horizontal flight by acting on the elevators and leaving the plane establish the equilibrium state again. However, usually, if we watch at an aircraft just after the take-off, for example, we do not observe a "phugoid" motion. This is essentially due to the possibility the aircraft to be longitudinally "trimmed". This trimming action on pitch is generated by regulating the elevators placed on the horizontal tail of the plane in order to lower or to lift up the aircraft tail inducing variations of the angle of attack. If the tail goes down (pulling the control yoke) the angle of attack increases and so does lift causing climb. If the trim is opportunely regulated during flight, the oscillations are damped much more quickly and we do not observe the "phugoid" motion. We have also upgraded our flight simulator by introducing the effect of trim. The results of simulation obtained by acting on the trim in such a way to contrast the plane tendency to oscillate are represented in the graphs of fig. 5a and b. The action of trim is well represented in the phase space as a "push" of the trajectory towards the equilibrium point. This is translated in the real trajectory as a quicker achievement of stable configuration. Compare, for instance, the climb of the airplane in a "untrimmed" situation with the trimmed one (fig. 5a, b).

4. – Conclusions

The flight simulator was employed with a group of 15 students enrolled in a graduate Physics Course for Secondary School Physics Teacher Preparation. All the students were graduated in mathematics and their university curricula included two physics courses. These consisted in lectures concerning the theory and applications aimed at the solution of quantitative problems without any laboratory activity. However, their initial ideas about the physics of flight were very vague. Students attended dedicated laboratory sessions where they worked in groups of two or three by analyzing the model and running the simulations to answer to problems, reported in individual work-sheets, outlining specific questions that would be discussed. Two teaching assistants co-operated with the course instructor in each laboratory session.

([2]) See for example the NASA technical paper downloadable at `http://www.nasa.gov/centers/dryden/pdf/87880main_H-953.pdf`

The analysis of student worksheets as well as of discussions with the students allowed to draw some conclusion about the pedagogical usefulness of the materials. The students showed a positive attitude toward such a didactical approach and a real interest in the concepts, models and approximations lying behind the process of simulating real-world systems. Student answers revealed a good level of understanding of the main concepts related to the physics of flight and a notable ability to differentiate the effects of the different physical variables. Moreover, the possibility of visualizing these effects played a relevant role in the student process of understanding of the dynamic properties of flight.

Finally, we have verified that simulation environments, as the one we have used, can bridge the gap between graphical, symbolic, and visual representations and these multiple representations contribute to meaningful learning.

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