Evaluation of the Flying Qualities of a Light Unmanned Airplane via Flight Simulation

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The purpose of the present work is to evaluate the flying qualities of the Unmanned Airplane for Ecological Conservation as a remote piloted vehicle via flight simulation. The study includes the evaluation of the interface and the display between the operator and the simulator. The model of the aircraft was simulated using FlightGear. Aerodynamic, geometric, thrust and mass characteristics of the airplane were introduced to the simulator by a code written in C++. Virtual flight trials were performed and the flying qualities were obtained through a “Briefing Guide and Rating Information for Simulated Handling Qualities Experiments Adapted for Remotely Piloted Vehicles.” It could be concluded that the Unmanned Airplane for Ecological Conservation has excellent flying qualities, rating the aircraft in Level 1. In addition, the interface with the operators was highly efficient because the display information contributes satisfactorily with the decision-making, rating the display as Level 1 on the Modified Cooper and Harper Evaluation Tool for Unmanned Vehicles Displays. The simulator is recommended to simulate flying qualities evaluation of unmanned aerial vehicles.

Nomenclature

FDM = flight dynamic model
OP 1,2 = observation Point 1, 2
PT 1,2 = pitch test 1,2
TP1,2,3,4 = turning point 1, 2, 3, 4
UAV = Unmanned aerial vehicle
RPV = Remote piloted vehicles
Vcr = cruise speed
Vy = best climb speed
Vyd = best descend speed

I. Introduction

In the last decade there has been an increase in the development and implementation of Unmanned Aerial Vehicles (UAVs). A matter of discussion is how the flying or handling qualities of these aircraft can be evaluated. Usually, this term is related to piloted planes, because they represent those characteristics that govern the ease and precision with which a pilot is capable of carrying out the task required in support of an aircraft role.

The classification of the flying qualities consists of qualitative evaluations. Supported by different quantitative studies that describe the performance of the airplane based on the evaluation of the response of the dynamic modes of motion of the aircraft in all their modes. The qualitative evaluations consist of the test of the plane in order to determine if it is capable of completing the task or mission required. The procedures for these tests involve the evaluation of the airplane performance during the flight, the capacity of the aircraft to fulfill the mission and the application of the Cooper and Harper Handling Qualities and Rating Scale.

Since unmanned airplanes do not have a pilot on board, it is very difficult to develop flight test techniques to evaluate the flying qualities. The operation control for unmanned aerial vehicles could be divided in two types:

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autonomous control and remote control.\textsuperscript{4} In the autonomous control, the vehicle does not depend of human control in any flight phase, and flying qualities refer mainly to the ability of the aircraft to navigate and operate over the indicated points and its capability to perform the mission.\textsuperscript{5} For this case, the manned flying quality evaluations do not apply and are not generally used. The remote control is referred to the remotely piloted vehicles (RPVs). This aircraft is controlled by a human pilot from a ground station, with the assistance of an on-board camera and the plane instruments. The interface of the ground station is very similar to the cabin of a manned plane. This has the conventional control driven by a set of joystick and flight instruments activated with the signal provided from probes in the plane. Based on these similarities, it is possible to complete a flying qualities evaluation of a remotely piloted vehicle with the same techniques of a manned vehicle. Then, the pilot opinion on the aircraft response characteristics is used to evaluate the flying qualities.

When the remotely piloted vehicles are operated it could occur that the ability of the system to support the operator with the proper information and the assessment in the decision-making is not accurate.\textsuperscript{6} For these reasons, it is necessary to create a display which allows obtaining information easily. This information has to be readily available to the pilot to facilitate his/her decision making. The tool to evaluate the interface between the operator and the vehicle must be capable of qualifying the control efficiency, analyzing the information of the flight instrument and its impact on the accomplishment of the mission. In this research, the Modified Copper and Harper Evaluation Tool for Unmanned Vehicle Displays was applied to evaluate the previously exposed mentioned topics.\textsuperscript{6}

The Unmanned Airplane for Ecological Conservation (ANCE) is an aircraft created to look at oil extraction facilities and pipelines in order to detect any leakages.\textsuperscript{7} The ANCE has a straight rectangular wing of 5.187 m of span and wing area of 3.1329 m\textsuperscript{2}, with a twin-boom tail configuration, driven by a pusher-propeller powered by a two stroke engine of 26 kW. It has a fixed landing gear and a ventral camera. The take-off mass is 182.055 kg, and the maximum fuel mass is 34.624 kg.

The ANCE static and dynamic stability had been studied via computational fluid dynamics. Cárdenas\textsuperscript{8,9} used the vortex lattice method to obtain the stability coefficients of the aircraft and evaluated the flying qualities using the criteria exposed by Prosser and Wiler.\textsuperscript{10} González\textsuperscript{11} employed the stability coefficients to model a half-geometry radio controlled version of the airplane in a flight model simulator and evaluated the flying qualities by the Cooper and Harper\textsuperscript{2} rate scale. In order to improve accuracy in the estimation of stability coefficient values, they were computed by a low-order panel method, and the static and dynamic stability were analysed.\textsuperscript{12}

The objective of this research is to evaluate the flying qualities of the ANCE as a remotely piloted vehicle via flight simulation. FlightGear\textsuperscript{13} is an open-source flight simulator used to perform the test with the open source Flight Dynamic Model JSBSim,\textsuperscript{14} because it allows the definition of aerodynamics and control and geometric characteristics of the airplane. Also, it is possible to modify the display presentation by the addition of different flight instruments. The gallery of sceneries facilitates the possibility of completing the flight test over operation areas, which increases the pilot confidence in the simulation.

II. Flying Qualities for Unmanned Aerial Vehicles

Due to the increase in the number of unmanned aerial vehicles, there has been an effort to develop the flying qualities analysis criteria in order to standardize these studies. There are a new set of topics to consider because the pilot is not on board. Prosser and Wiler\textsuperscript{10} proposed the criteria to evaluate the performance of a remotely piloted vehicle during a mission and the requirements of the systems regarding automatic and manual control, as well as vehicle stability and control.

Breneman and Lower\textsuperscript{4} presented some techniques to facilitate the quantification of UAV flying qualities data. Initially, they approached the manned airplane flying qualities techniques to the evaluation of the UAVs, applying the Cooper and Harper Handling Qualities Rating Scale\textsuperscript{2} and mission relatable tasks. The analysis was completed with the quantification of the vehicle physical performance. Thus, it is essential that the information be provided to the operator clearly and efficiently. Cummings et al.,\textsuperscript{15} modified the Cooper and Harper rating scale to present an evaluation tool for unmanned vehicle displays to ensure they provide operators with sufficient information for effective mission performance.

The flying qualities criteria is still considered deficient for UAVs because they rely on manned aircraft considerations. For this reason, Holmberg et al.,\textsuperscript{2} and Hameed et al.,\textsuperscript{15} presented a development of new flying qualities criteria, specifications and design standards for unmanned aerial systems. Owing to flying qualities requirements, tests and evaluation tools are in continuous development and discussion. Cotting\textsuperscript{3} defines a series of categories to classify unmanned aerial vehicles for flying qualities analyses.
III. Piloted Simulation Trials

The objectives of these simulated trials are to observe and qualitatively comment on the flying qualities of the ANCE, and to evaluate the pilot-vehicle interaction and the display presentation. Before the flight tests are performed, the pilot is introduced to the airplane capabilities and expected mission performance; also, a set of performance characteristics is given to him/her, operation speeds, altitude and flying procedures. Then, the interface, control sticks, and instruments are presented. For these trials, and expecting to increase the fidelity of the controls of the plane, the CH Products Flight Sim Yoke was employed with control channels for elevator and aileron stick and trim control, levers for throttle variation and mixture control, and a camera control are also available. For rudder control with differential brake capacity, the CH Products Pro Pedals system was used. Figure 1 shows the flight simulator suite. The aeronautical charts ONC Sheet K-2616 and ONC Sheet K-2717 and Google Earth application were used to define the routes of trials.18

The trials had been divided in a series of three different simulated flight tests. Flight Test 1 was designed to evaluate the lateral-directional flying qualities of the ANCE. Flight Test 2 was designed to evaluate the longitudinal performance of the airplane. Flight Test 3 intended to subject the ANCE in a reconnaissance mission where it must complete two different scout patterns over different targets. The pilot must focus his/her analysis on four different factors. The first one, the static stability response of the plane with stick-fixed and stick-free, to avoid any unsafe flight condition; the second is the dynamic response for a proper damping of any disturbance ensuring an appropriated response to guarantee the airplane has the ability to complete a task. The third is the control feeling and reliability, which must be considered during the flight phases; display veracity, simplicity, and precision of the data presented in the display must be taken into account; this factor is used to determine the capability of the operator to control de airplane. The fourth factor takes place during take-off and landing; the control requirements have to guarantee control power for rotation and for handling crosswinds, but not for evaluating the pilot control force requirements, to ensure safe, precise, and accurate take-off and landing.

Finally, the operator is subjected to the Cooper and Harper Rating Scale2 to evaluate the flying qualities of the ANCE. The display and the operator simulation interface were evaluated using the modified Cooper and Harper tool for unmanned vehicle display.6 To carry out the evaluation, the operators were selected based on their flight experience. To estimate the flying qualities of the ANCE the “Briefing Guide and Rating Information for Handling Qualities Experiments”24 was modified to evaluate simulated remotely piloted vehicles. This inquiry has the intention of getting the pilot’s opinion about the flying qualities and performance of an airplane under different missions, tasks, and atmospheric conditions (Appendix A).

A. Virtual Flight Test 1

It had the main objective of familiarizing the pilot with the airplane and evaluating qualitatively the flying qualities of the ANCE on turn maneuvers.

The test is performed from the virtual Oscar Machado Zuloaga airport in Charallave, State of Miranda, Venezuela, and it follows the route shown in Fig. 2. One requirement is that all turn maneuvers had to be completed without sideslip. The test had an approximate duration of forty minutes. The pilot had to evaluate the ground performance of the ANCE from the taxiway to the runway. Once this was achieved, the pilot had to complete the next series of tasks:

1) Complete the take-off at the respective speeds.
2) Climb at $V_s$ speed and obtain level flight at $V_{cr}$ at 3500 ft.
3) Develop a traffic pattern over the runway testing and becoming familiar with the controls.
4) Climb to 5000 ft at $V_y$. 

Figure 1. Flight simulator suit using during the tests
5) Complete the traffic pattern over the runway at $V_{cr}$, initially to the right side and then to the left. The turn must be increasing in its roll angle the first turn at “TP$_1$” 5 deg, and then consecutively “TP$_2$” 10, “TP$_3$” 20 and “TP$_4$” 30 deg; the pilot must adjust power and speed to ensure no sideslip.

   6) Climb at $V_y$ and obtain level at cruise altitude of 8000 ft.

   7) Complete the traffic pattern, bank angle capture tasks, aileron only, and then rudder only turns.

   8) Set up approach to landing at the required $V_{sy}$. 

   9) Complete landing and parking of the aircraft.

B. Virtual Flight Test 2

This had the purpose of observing and qualitatively commenting on the flying qualities of the ANCE during a medium range flight route, by following and maintaining a flight path, while different longitudinal evaluations are performed.

Figure 3 illustrates the route of Flight Test 2. This took place in the Oscar Machado Zuloaga virtual airport in Charallave, State of Miranda, Venezuela. Route A involved the distance between Charallave airport and the Higuerote airport. Route B, from Higuerote airport, in Higuerote, State of Miranda, Venezuela, to the Codera Cape. Route C covers the distance between the Codera Cape and the Simon Bolivar airport in Maiquetia, State of Vargas, Venezuela. The test lasted approximately two hours. The pilot had to complete the next series of tasks:

1) Complete the take-off at the respective speeds.

2) Climb at $V_y$ speed and obtain level flight at $V_{cr}$ at 3500 ft.

3) Perform turn to start Route A.

4) Adjust trim and level at 5000 ft.

5) Pitch Test 1: consist in the variation of the pitch angle from 0, 5, 10 to 12 deg and holding each one of them during one minute, adjusting velocity to ensure no altitude variations.

6) Climb to cruise altitude and repeat Pitch test 1.

7) At the end of route B, it is necessary to complete an approach and perform a touch and go.

8) Change course and complete Route B climbing to cruise altitude.
9) Change course and engage Route C.
10) Pitch Test 2 consists of a swift variation of the pitch angle through the next sequence 0, 5, 10, 15, 0, –5, –10, –15, 15 deg and to observe the reaction of the airplane with stick-free.
11) Repeat Pitch Test 2 with stick-fixed at zero degrees.
12) Set up approach to landing at the required \( V_{yd} \).
13) Complete landing and parking of the aircraft.

C. Virtual Flight Test 3

This had the purpose of observing and qualitatively commenting on the flying qualities of the ANCE during a medium range reconnaissance mission where the operator must complete two different search patterns over another target over the flight route. Figure 4 presents the route of Flight Test 3. The trail took places from the virtual international airport General Santiago Mariño Porlamar, State of Nueva Esparta, Venezuela. The test lasted approximately forty minutes. The operator had to complete the next series of tasks:
1) Perform a proper take-off at the respective speeds.
2) Change course to observation point 1 (OP1) in Coche Island, climb and level at 2500 ft.
3) Arrive to OP1, then, the airplane must fly over a fixed target in the simulator environment in an orbital pattern at constant altitude and constant bank angle.
4) Change course and head to OP2 in Cubagua Island.
5) Over the OP2, the airplane must fly over the target in an X-pattern at constant altitude.
6) Set up approach to landing at the required \( V_{yd} \).
7) Complete landing and parking of the aircraft.

IV. Flight Simulation of the ANCE

The simulation as a remotely piloted vehicle of the ANCE was performed with FlightGear, an adaptable open source flight simulator. This simulator has relatively low system requirement and the capacity to process a wide range of aircrafts. The code has a large quantity of sceneries that allows performing the flight tests over the expected service area of the ANCE.

The flight dynamic model (FDM) selected for this simulation was JSBSim. This is a collection of codes written in programming language C++ with some routines in C language. It models the six rigid-body degrees of freedom, solving the aerodynamic forces and moments over the aircraft using a classical coefficient build-up method.
resolving the equation of motion through a matrix of quaternions. It calculates the velocity, position and orientation of the airplane in discrete time steps.\textsuperscript{14} The aircraft, engine, and control models are introduced to the JSBSim through a series of files in “.xml” extension. Sorton\textsuperscript{15} concluded that there is a good level of correlation between the simulator with this FDM and the real performance of a light UAV.

The model file of the ANCE in FlightGears is composed by different sections with the purpose of defining the components of the airplane. The main file defines the characteristics of the airplane, dimensions, mass, inertia distribution, and fuel mass location. The ground reactions of the geometry are assigned to the file, in order to determine the geometric references and limits of the model. The position and orientation of the propeller and the engine are defined too. The characteristics of flight control movement and range of action were inserted. The aerodynamic and stability coefficients shown in Ref. 12 were included to the aerodynamics characteristic in this file.

The geometry of the ANCE is defined in the main “.xml” file. The hard points or points of contact of the geometry with the environment of the simulator possess their own characteristics of location, static friction and dynamic friction, rolling friction, damping and spring coefficients. The coordinates of these hard points are referenced to an “.ac” extension file that contains the geometry of the plane. The geometry of the ANCE was created in Blender, an open source three-dimensional design program capable of generating virtual solids with a high level of detail.\textsuperscript{20} The axes and coordinates between the FlightGears and Blender must be adjusted before loading the file. The hard points of the ANCE include the wing and empennage tips, the nose, the superior and inferior points of the fuselage, main landing gear and the nose wheel, the capability of the nose wheel to turn at the same rate that the rudder was also included.

Another “.xml” was used to describe characteristics of power, revolutions per minute (RPM) and rate of acceleration of the engine. The propulsion system of ANCE is composed of a 5868-9 two blade propeller\textsuperscript{21} driven by a Cuyuna 460F-35 (Ref. 22) engine of 26.1 kW. The propeller file was created including the thrust and power coefficients and the dimensions of the blade.

A set of instruments were added to the aircraft model keeping the disposition and presentation laid out in a manned airplane. The instruments installed were fixed into the display of the simulation arranged in a basic “I”. The instruments included were the attitude indicator, the vertical speed indicator (rate of climb), the altimeter, the directional gyro (compass), and the turn and bank indicator (aircraft attitude). The virtual flight instruments were loaded in files “.xml” extensions, and the related geometry with each instrument was loaded with an “.ac” extension. To increase the fidelity of the display and the simulation, the RPM counter and the fuel indicators were included. Figure 5 presents the display of the simulated ground station, and Fig. 6 shows the ANCE model in FlightGears.

V. Results and Discussion

After each flight test was completed, the operators were questioned above the performance of the ANCE model in FlightGear. For the first factor, the evaluation the operators did not report any problems, the aircraft retained static stability with stick-fixed and stick-free at all times. For the second factor, the responses to the dynamic modes observed were considered convergent and dampened to all disturbances. The longitudinal modes always tend to decrease the pitching angle. The spiral modes tend to pull out the aircraft from the spiral divergence. Performance was not affected by the Dutch roll. The operators report that the aircraft posses a proper quick response to reject any disturbances.

For the third factor, the performance and the manoeuvrability of the airplane were very acceptable for the mission requirements. The aircraft was capable of sustaining the required speed for every task and flight phase. Longitudinal and directional trim were highly satisfactory during the manoeuvres, facilitating the climb procedures and compensating the engine torque during turn manoeuvres. Even though stall or spins were induced by the operators, they were capable of gaining control and levelling the airplane. The conditions on the flight envelope were evaluated. The change of the thrust with the variation of the throttle was appreciable. The fuel mixture could be changed, improving the performance of the aircraft when it increases altitude.

For the fourth factor, the aircraft shows an adequate performance during the approximation; it has the ability of maintaining a glide slope and of completing flare maneuvers with a high level of precision. The rotation and take-off speeds were compared to those estimated analytically and they are in good agreement.

During the flight test, the aircraft shows a good capability of sustaining heading and following routes. The airplane was capable of fulfilling a recognition mission over the fixed observation points with two different patterns without increasing the operator workload.
When the trials finished, the operators rated the airplane employing the Cooper and Harper scale. They rated the ANCE as Level 1. They described the aircraft as controllable during the maneuvers; it did not cause any intolerable pilot workload, and they considered it satisfactory without improvement. Furthermore, they rated the used display as Level 1, because it allows acquiring the information easily, and it was enough to analyze the flight situations and to facilitate efficient decision-making.

The confidence factor on the simulation was evaluated. During the tests, the change in performance was sensed with the variation of thrust, aircraft orientation, and atmospheric conditions. An excellent correlation was found between the surface control movements and the aircraft reactions. The stall was perceptible in the simulator and the performance of the aircraft adapts itself very well to the flight envelope. The flight routes and heading are correlated with those on the flight charts. The confidence factor of FlightGear was rated as class A simulator, because it has a relatively high degree of confidence.

**VI. Conclusions**

This investigation evaluated the flying qualities of an RPV through a simulated flight test. A model of the aircraft was created on FlightGear with the flight dynamic model JSBSim. An interactive display was designed with the operators; to improve the interface with the aircraft, a set of instruments and joystick were adapted to increase the capability of control in the proposed ground station.

Once the tests were completed by the operators, it is possible to conclude that the Unmanned Airplane for Ecological Conservation is easily maneuverable and it has excellent flying qualities; it was rated as Level 1 with the Cooper and Harper Scale. In addition, the interface with the operators was highly efficient; the display information contributes satisfactorily to the decision-making; this rates the display as Level 1 on the Modified Cooper and Harper Evaluation Tool for Unmanned Vehicles Displays. The simulator demonstrated a high degree of confidence and its confidence factor is Class A.
Appendix A

Procedure for the application of the Briefing Guide and Rating Information for Simulated Handling Qualities
Experiments Adapted for Remote Piloted Vehicles

A) Factors to consider during the flight tests: These factors are specified to adjust the evaluation criteria over the different flight tests.

1) Static Stability. This requirement must be accomplished with stick-fixed and stick-free to continue the test and is mandatory to avoid any unsafe condition.

2) Dynamic Modes of Response. Phugoid stability evaluation is also required to determine if there is a proper damping of any longitudinal disturbance. In addition, spiral modes must be evaluated to ensure safe operation of the airplane. Short period, Dutch roll and roll mode criteria for the remotely piloted vehicles are designated to ensure an appropriate quick response, keep the operator from inducing oscillations, a good disturbance rejection and guarantee that the aircraft response does not degrade the ability to control the aircraft and complete the task.

3) Control Capability. Longitudinal control must be evaluated during all phases of the test. Pitch control cannot exceed the load factor of the flight envelope. However this must not limit the operator from attaining all airspeeds. Does not limit take-off performance or cause over-rotation. Lateral-directional control must ensure any yaw or roll maneuver avoiding or controlling sideslips and roll angles with crosswinds.

Control feeling and liability must be considered during all flying phases. Display veracity, ease and precision of the data must be taken into account. These topics are intended to determine how well the operator controls the aircraft. This section also includes instrument display interaction, capacity for recovery from stalls, out of control flights and spins, stabilization and navigation capabilities.

4) Take-off and Landing. The control requirements will still need to ensure control power for rotation and to handle crosswinds, but a pilot control force requirements are not applicable, and it is necessary to ensure safe, precise and accurate take-offs and landings.

B) Description and familiarization. This section is suited to familiarize and describe the aircraft to the operator. Geometrical characteristics, expected missions and flight capabilities. Performance, description of the airplane, flight envelope, maneuvers diagram, take-off and landing procedures.

C) Description of the flight test.

1) Mission requirements and factors to evaluate.

2) Conditions of the test; location, atmospheric and aircraft conditions.

3) Operator interface, Display, available instruments and controls.

4) Mission routes and waypoints coordinates with the respective chart of the area.

D) Commentary on every topic

1) Static Stability;

2) Dynamic Modes Response:

3) Control Capacity:

4) Take-off and landings:

E) Post Flight Enquiry

1) Is the aircraft controllable?

2) It is capable of fulfilling the mission with an adequate mission performance?

3) Is the aircraft performance adequate with a tolerable pilot workload?

4) How is the relationship between the control and the movement of the airplane?

5) Is the signal introduced by the control satisfactorily translated during the simulation?

6) How real was the simulation? Is the simulated flight comparable to a real one?
7) Was there any deficiency with the instrument or the display? ____________________________

8) Comment on the instruments performance and the display:________________________________

Application of the Cooper-Harper Handling Qualities Rating Scale. (____).
Application of the Modified Cooper Harper Evaluation Tool for Unmanned Vehicle Display. (____).
Pilots Confidence Factor on the Simulation. (____)
F) General Remarks and Comments on the flying qualities or the RPV, the interface and the display.

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