COMPUTATIONAL SIMULATION OF AN AIRCRAFT CABIN PRESSURE CONTROL SYSTEM

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Abstract. *In the context of aircraft cabin environmental control, the goal of this work is to build a mathematical model of the cabin pressure control system and to simulate it for some important design cases. The developing of the model is based on the recommendation document ARP 1270 (SAE, 2000) with some modifications in order to apply it to a specific aircraft design, developed in academic work. From the model of the cabin pressure control system built for this aircraft, normal flight operation (climb, cruise and descent) and some failure cases are simulated. The first failure event studied is when the outflow valve fails open and the cabin depressurizes. The second one is the failure of the outflow valve in the closed position, with continuous increase of the cabin pressure, and the third failure case is the complete loss of the pneumatic system, another depressurization case. These cases are especially interesting in the initial analysis of the system, allowing the preliminary design of the aircraft's emergency descent profile (depressurizing cases) and safety valve, that prevents great pressure differentials on the cabin (outflow valve fail closed).*

Keywords: *ecs, cabin pressure, control system, simulation*

1. Introduction

Aircraft environmental control systems provide appropriate cabin environmental conditions for survival and comfort of passengers and crew, comprising the pneumatic (bleed) system, air conditioning, cabin pressurization and supplemental oxygen. This work is dedicated to the study of a cabin pressure control system through computational simulation of its dynamic response. Simulations here presented are based on the concept of a very light jet, a purely academic design developed during the Engineering Specialization Program, a Professional Master Degree course in partnership between ITA and EMBRAER S.A.

Ambient pressure decreases rapidly with altitude and it is not satisfactory to human physiological breathing needs at high altitudes, oxygen partial pressure in the air is very low and the body is not able to adequately supply cells and tissues with oxygen. This lack of oxygen in the blood causes some important effects on human bodies varying from a simple headache and discomfort at relatively low altitudes, 3048 to 4572 m (10000 to 15000 ft), to total loss of consciousness, above 7620 m (25000 ft). Other effects of low ambient pressure levels on human body are expansion of gases in cavities (sinus, abdomen) and dissolved in the blood (nitrogen) that may cause more serious problems.

Another physiological problem concerns cabin pressure changes, related to the middle ear equalization through the Eustachian tube. The source of these effects fall into two broad categories: pressure transients (bumps) and slower pressure changes. Pressure bumps are short duration cabin pressure changes of sufficient magnitude to cause passenger pain and discomfort. Proper design of the controls and equipment of the air conditioning and pressurization systems can minimize bumps and significantly enhance passenger comfort. Concerning slower steady pressure changes, studies have shown that acceptable rates of cabin climb and descent are typically in the range of 1.524 to 2.54 m/s (300 to 500ft/min). The Equivalent Eardrum Differential Pressure is a well accepted design reference for pressurization systems. This method considers the sensory perception of the average individual on the basis of time integration of the eardrum differential pressure due to rate changes. It is based on a fixed physical model of the human ear and gives results similar to those shown in Fig. 1.

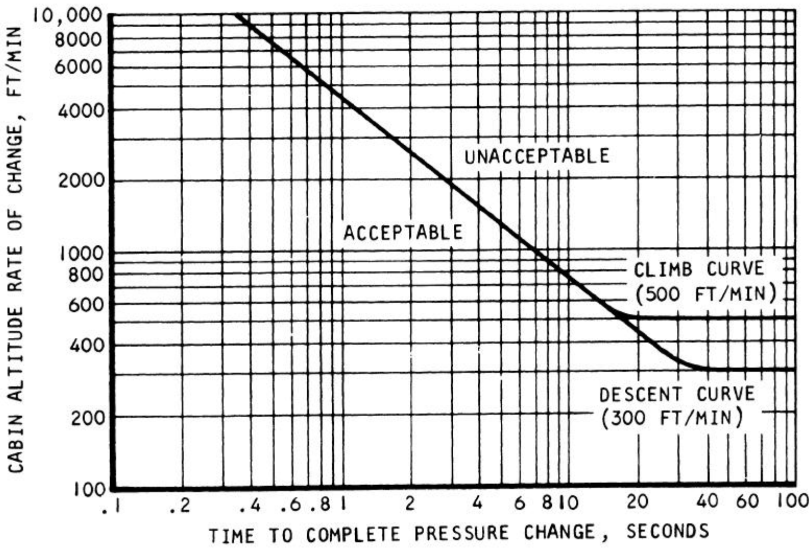

Figure 1. Acceptable cabin climb and descent rates, SAE (2000)

Thus, the goal of pressurization control systems is maintaining cabin environment with physiological adequate levels of ambient pressure, controlling rates of pressure changes within acceptable limits. The problem of aircraft cabin pressurization has been studied since around 1920, but the first airplanes equipped with this kind of system were the latest generation of bombers of the Second World War.

Pressurization systems in general use bleed air from the engines to maintain cabin pressure higher than ambient, controlling it by modulating the exhaust flow through the outflow valve. The several types of systems can be classified through the source of energy that drives the outflow valve, basically: pneumatic, electro-pneumatic and electronic systems. In the electronic systems, all control and valve actuation functions are performed with electrical power. The cabin pressure controller unit is electronically modulated, incorporating a pressure sensor, a signal generator and logic circuit. The controller receives signals from the Flight Management System or from the pilot (for take-off and landing altitudes, for instance) and sends another signal for the electric actuator of the OFV, commanding its position and, consequently, the exhaust flow.

Every non-experimental aircraft designated to transport people must attest its safe and reliable operation through certification authorities. These are civil entities that combine the interests of aircraft manufacturers, passengers, airline companies, pilots and attendants and formulate a set of regulations that drive the design, construction and operation of the aircraft. In Brazil, this activity is made by the Centro Técnico Aeroespacial (CTA/IFI) and in the USA by the Federal Aviation Authority (FAA). Among the certification rules formulated by these authorities, this work is aimed on section 841 of both FAR Part 23 and 25, referring to the North American rules, which are very similar to the Brazilian ones. Although the aircraft over this work is based on shall comply with Part 23 requirements (maximum weight less than 13,000 lb), the system design requirements presented are from Part 25. This is due to the fact that small jets are generally asked by the certification authorities to comply with some Special Conditions that make the final requirements equivalent to the more stringent Part 25.

These certification authorities also issue Advisory Circulars (AC), which are documents that suggest (not mandatory) procedures and equipment to comply with certification rules integrally. The AC 25-20, FAA (1996), recommends an emergency descent profile as a means to comply with certification requirements in case of cabin depressurization. This procedure will be followed in this work and its graphical representation included in the AC document is shown in Fig. 2. The figure shows the aircraft initially in stabilized flight at 12497 m (41000 ft) with cabin altitude at 2438 m (8000 ft) until T_f, when the failure event occurs and cabin altitude starts to increase. Instants after, at T_W, the 3048 m (10000 ft) aural warning is on and a 17 second delay (AC recommended value) for pilot situation awareness and emergency descent configuration set up is considered before T_I, when the descent begins. Figure 2 also shows the criteria to be complied in the emergency descent procedure: cabin altitude must not remain above 7620 m (25000 ft) for more than 2 minutes and above 12192 m (40000 ft) for any time.

Modeling and simulation of aircraft environmental control systems in the literature are concentrated in air conditioning and thermal load areas. A thermal transient model of the cabin can be found on the works of Fang (1999) and Zaparoli and Andrade (2003). Other studies of cabin thermal models and thermal comfort coupled with cabin temperature control design are found on Hofman (2003) and Turcio e Neto (2003). Studies on pressurization systems modeling, control and simulation are very rare in the literature, reserved mainly to manufacturer's technical domain and property. The only study found on this subject corresponds to the recommended practice document from SAE, ARP 1270 (SAE, 2000).

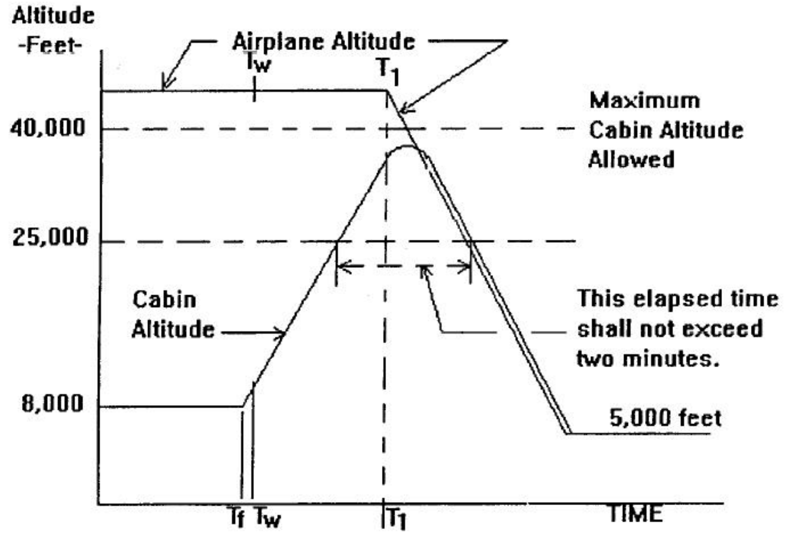

Figure 2. Aircraft general emergency descent profile, FAA (1996)

2. Methodology

The development of the mathematical model herein is based on document SAE (2000), where the global model of the pressurization system is presented at first followed by each specific component of the system.

2.1. Mathematical model of the pressurization system

The pressurization system can be mathematically represented in terms of mass balance of the air entering and leaving the cabin control volume. Air inside the cabin is considered perfect gas, described by the state equation:

$$P_c V_c = m_c R T_c \tag{1}$$

Where P_c is the air pressure inside the cabin, V_c is the cabin volume, m_c is the mass of air inside the cabin, R is the specific gas constant and T_c is the cabin temperature. Time variation of the mass of air inside the cabin is obtained deriving Eq. (1), considering a fixed cabin volume and constant temperature. Applying the mass balance on air in the cabin, the only airflow entering corresponds to the air conditioning inflow, W_i (from pneumatic system). The total airflow leaving the cabin is the sum of the controlled exhaust flow through the OFV, W_o, and uncontrolled leakage from the pressurized cabin, W_L. The mass air inflow minus the sum of outflow equals the time variation of the mass of air inside the cabin. Thus:

$$\frac{V_c}{RT_c}\frac{dP_c}{dt} = \frac{dm_c}{dt} = W_i - W_o - W_L \tag{2}$$

Rearranging Eq. (3) to an integral equation for the cabin pressure, it gives:

$$P_c = \frac{RT_c}{V_c}\int (W_i - W_o - W_L)dt \tag{3}$$

Figure 3 shows the block diagram representing the mathematical model of the pressurization system built in Simulink© Matlab©. The diagram has an input block that gives the cabin altitude reference, set of data specified by the user, to be compared with the actual cabin pressure, measured by cabin sensors. This error signal is fed into the controller block, which processes it and sends a command signal to the outflow valve. The resulting position of the outflow valve corresponds to a certain value of exhaust air, which is algebraically summed to the leakage and the inflow. The inflow is a user defined value and the leakage depends directly on the particular aircraft and pressure differential applied on the cabin. The resulting mass flow is then integrated to obtain the mass of air inside the cabin and the perfect gas relation gives the corresponding cabin pressure, which is the feedback in the closed loop control system.

The integrated valve and actuator model represents a butterfly outflow valve commanded by a DC electric actuator. The block shown in Fig. 3 (outflow valve and actuator models) comprises the dynamics of the actuator and opening characteristics (position versus resulting flow) of the valve. The signal leaving the controller is proportionally transformed into position reference command for the actuator in the 0-90^o (full open to full close). This feature also represents the physical limits of the valve, avoiding the simulation to produce unreal, out of range valve position values.

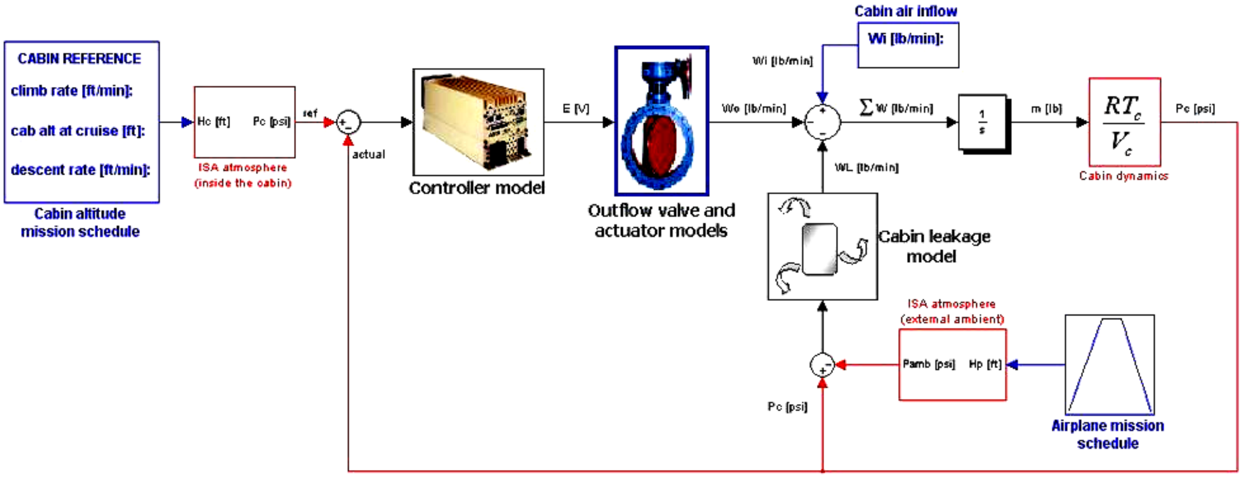

Figure 3. Block diagram of the cabin pressure control system

The actuator dynamics is considered to be a second order transfer function, as recommended per SAE (1994), with internal position feedback and a linear relationship between torque and velocity. The above reference also recommends values of 0.02 and 0.001 s for the mechanical and electrical time constants, respectively. Equation (4) shows this transfer function, where θ_o is the valve position, θ_i is the input electrical signal (position reference), K_v is the actuator gain, τ_m and τ_e are the mechanical and electrical time constants.

$$\frac{\theta_o}{\theta_i} = \frac{K_v}{s(1+\tau_m s)(1+\tau_e s)} \tag{4}$$

The actuator gain K_v is adjusted following performance specifications of the valve, based on its step response. As a typical number used in industry, the valve velocity cannot exceed 9^o/s (0.157 rad/s), for mechanical purposes, any time. This is the value adopted in this work, when the valve is commanded from the full open to full close position. The resulting valve then presents a behavior similar to a first order system, with the response reaching half of its final value in 7 s and 90% of its final value in 22 s. After the actuator dynamics, a simplified linear opening characteristic is considered for the valve, where the exhaust flow is zero for a butterfly angle of 90^o and equivalent to the total air inflow when the valve is full open, zero degree.

Still in Fig. 3, the Cabin Altitude Mission Schedule and Airplane Mission Schedule blocks are user defined inputs, depending on the performance characteristics of a particular aircraft. Cabin Air Inflow is also an input block and is considered constant here in this work with the minimal value (0.0042 kg/s, 0.55 lb/min, per occupant) following certification rules. Cabin Leakage Model is based on the concept of fuselage critical hole, which is an equivalent opening area on the pressurized vessel where the uncontrolled leakage of the cabin is concentrated. The final leakage flow value is dependent mainly of manufacturing quality and the differential pressure on the cabin.

2.2. Controller model

The controller is initially designed considering a non-disturbed, linearized system around the point represented by cruise flight operation, satisfying the desired system performance specifications. The initial design is then obtained and tested for the non-linear plant, if the dynamic response in all normal operation conditions is considered to be satisfactory, it is retained as the final design.

The root locus analysis of the linear system shows that the two poles more on the left of the origin (-1000 and -50) keep on the stable region for any positive value of K_c. However, the pole on the origin and the one closer (-0.01) lead the system to the instability region as K_c increases above a certain value. The analysis shows that the system is stable, all poles are negative, approximately in the range $0<K_c<3300$. The non-linear plant is then tested with a single gain (proportional) controller varying over this range.

For this test analysis, two performance requirements must be fulfilled in a specific flight condition: stabilization in transition from climb to cruise at 10668 m (35000 ft) flight level and 1829 m (6000 ft) cabin altitude pressure. The final static error between reference and actual cabin pressure shall be less than 18 m, 60 ft, (1%) and the system shall reach steady state condition with less than three periods of oscillation. The analysis show that no simple gain can meet these requirements, a lower gain values produce a good transient behavior, few or no oscillations, but steady state cabin pressure values far beyond the requirement. Higher gain values result in almost zero steady state error, but prohibitive oscillations.

A PID controller will then be adopted. Using a sequential attempt and optimization method, the controller proportional, integral and derivative constants are obtained and the final result is presented in Fig. 4. It shows the system cruise stabilization dynamics, where the red line is the cabin altitude reference and the blue one the system response. It can be observed that the steady state error is very low for a two-period oscillation stabilization.

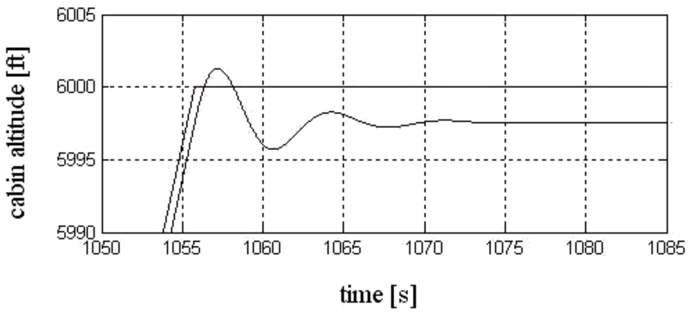

Figure 4. System response with the PID controller

3. System simulation

3.1. Normal flight operation

The global model is then used in the simulation of a complete flight case, climb, cruise and descent. Ground operations like take-off run and taxi are not the aim and will be left aside for future works. The mission profile adopted corresponds to a typical one for this kind of airplane operating as an air taxi, with climb to cruise at 10668 m (35000 ft) and total duration of about 60 min. Figure 5 represents the transient response of the system in the beginning of the climb phase (take-off at 244 m, 800 ft, with -61 m, -200 ft, of pre-pressurization), showing acceptable oscillations and a maximum error between real cabin altitude and reference of 2.7 m (9 ft).

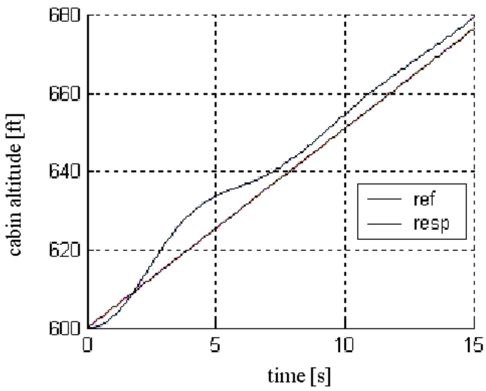

Figure 5. Cabin altitude climb simulation

Figure 6 shows the dynamic behavior of the cabin altitude rate of climb. The rate stabilizes at 1.56 m/s (307ft/min) in about 20 s. It can be observed that the peak value of the rate is 3.175 m/s (625 ft/min), but it is acceptable because it occurs during a very short period of time, the rate stays higher than 2.54 m/s (500 ft/min) for just 3 s. Consulting Fig. 1, it can be seen that, for a three second period of time, rates until 10.16 m/s (2000 ft/min) are acceptable.

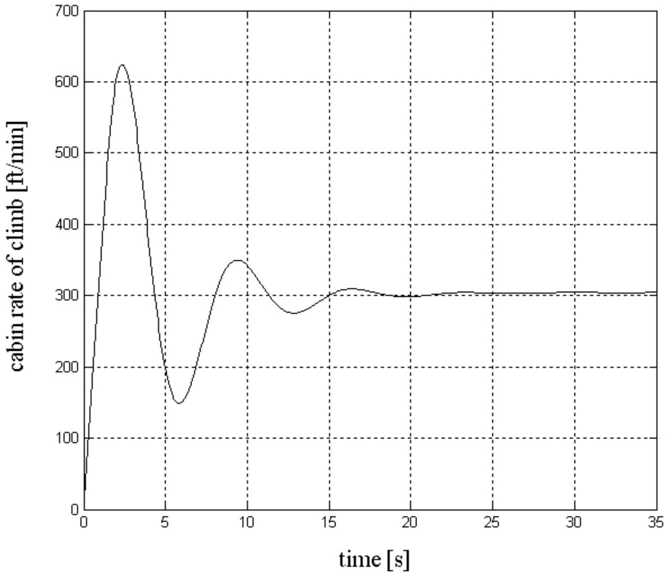

Figure 6. Cabin rate of climb stabilization

The transition from climb to cruise flight is exactly the situation considered for the controller design, shown in Fig. 4. Transition from cruise to descent is similar to the beginning of climb, again the transient rates are acceptable and maximum error is less than 1.52 m (5 ft). The steady state cabin descent rate is 1.83 m/s (360 ft/min), above the limits from Fig. 1. This value is maintained, though, in order to preserve the aircraft descent performance.

The valve position is shown in Fig. 7, where zero corresponds to full open and 90^o full closed. It can be seen that the valve closes rapidly at the beginning and transitions to and from cruise condition with acceptable oscillations (details). It is important to notice that the valve angle during more than 90% of the total operation time is higher than 45^o, more to the closed position. It is a good design behavior, once the torque caused by the airflow through the valve tends to close it (the safe position) during almost all the time.

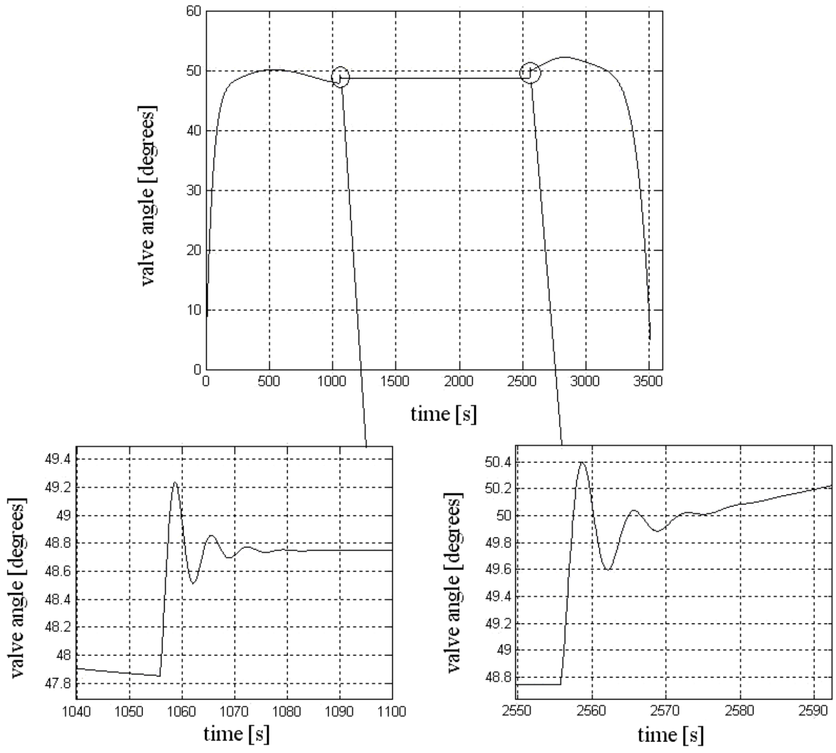

Figure 7. Outflow valve position in normal flight simulation

3.2. Failure cases

The study of valve failure in full open position considers cabin decompression in the aircraft operational ceiling, 12497 m (41000 ft). The flight profile is similar to the normal operation case studied before, but cabin altitude is 2438m (8000 ft) at this flight level. To simulate the failure, three minutes after stabilized (cruise) flight the valve is commanded instantaneously to full open and keeps locked in this position. Figure 8 illustrates the dynamic behavior of the cabin in this situation.

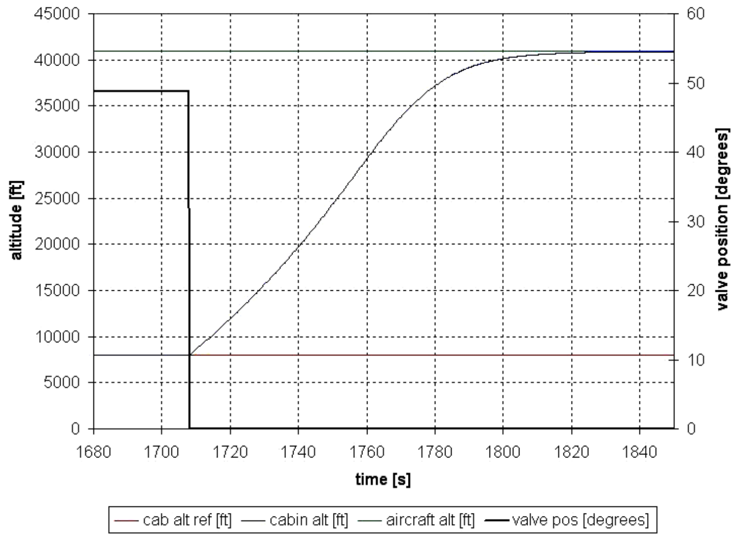

Figure 8. Simulation of outflow valve failed in full closed position

It can be observed that the decompression is very rapid, the cabin altitude reaches 7620 m (25000 ft) and 12192 m (40000 ft) in 43 and 90 s after the failure, respectively. To comply with certification requirements, an emergency descent shall be performed, as explained. When cabin altitude reaches 3048 m (10000 ft), an aural warning is activated. From this time on, a delay of 17 s is considered as reaction time for the pilot to recognize the situation and put on the oxygen masks. Additionally, 10 s is considered as supplementary preparation for the descent and to have some margin. Figure 9 shows the emergency descent pressurization profile, from descent beginning around instant 1735 s (T_1 on Fig. 2) until 3048 m (10000 ft) depressurized flight. The descent is designed so that the cabin altitude remains 2 min above 25000 ft, never crossing the 12192 m (40000 ft) limit. For this particular failure event, the minimal aircraft emergency descent rate is calculated to be 41.7 m/s (8200 ft/min).

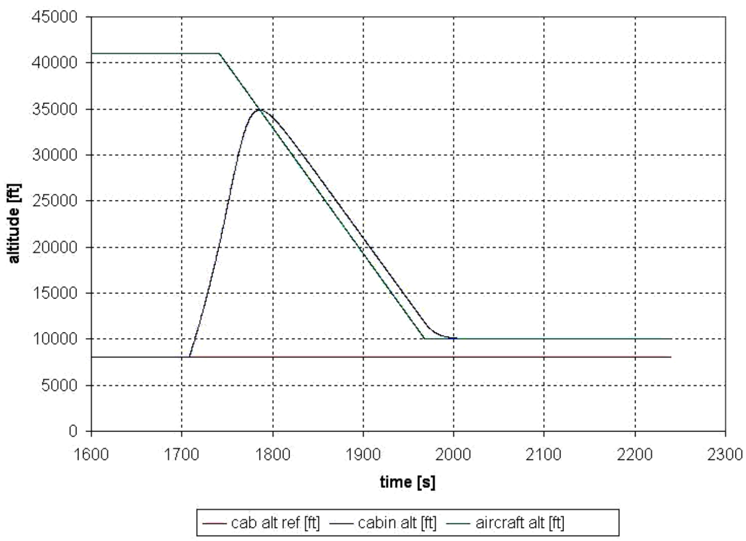

Figure 9. Simulation of emergency descent for the outflow valve failed in full closed position

The other possible failure causing cabin depressurization and thus demanding an emergency descent is total loss of the pneumatic system, the source of compressed air to pressurize the cabin. In this case, the automatic control system commands the valve to full closed position, but cabin leakage still contribute to depressurization. Cabin altitude reaches 12192 m (40000 ft) faster in this case, in 82 s. The emergency descent design and graph is similar to the previous case, and the aircraft rate of descent required for this case is higher, 42.4 m/s (8350 ft/min), which is the one that should be adopted as a design requirement.

Finally, the outflow valve failure in closed position represents the less critical case, no pilot actions are required and the positive relief valve avoids cabin differential pressure to rise above a structural safe limit. Simulations of this case show that the valve must relieve the cabin very quickly, once the differential pressure limit (5% above the maximum, 57364 Pa, 8,32 psid) is reached only 4 s after the outflow valve failure.

4. Conclusion

Three basic cases concerning pressurization systems were studied in this work: normal operation, valve failure and loss of all pneumatic sources. By the normal operation simulation, it was verified that an appropriate controller design was reached, satisfying all flight cases. The depressurization critical failures required emergency descent simulations and they estimated a value of minimum aircraft emergency rate of descent. This is a very important interface value between environmental systems and aerodynamics in the preliminary design of an aircraft.

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