Design of Altitude Measurement System for Aerospace Applications (Digital Barometric Altimeter)

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Abstract—Altimeter is a measurement system that is used to determine the altitude of a flying vehicle. It provides the aircraft pilot, navigator and other aerospace users with the altitude information, either in analog or digital readout. This information is a very important parameter for aerospace users during flight in order to achieve safe and efficient flight operation. Therefore, using an accurate method for altitude measurement is essential. The altimeter system may subject to many sources of errors (methodical, systematic and dynamic) during operation, due to the integration of aircraft instrument system, the altitude information should be accurate more than ever before, and so as to provide the actual altitude to other integrated systems. Thus a new digital altimeter is significant and much needed for this reason, to enhance the old conventional system.

This paper focuses on diagnosing of conventional altimeter errors and expresses in mathematical derivations, compensate these deviations of the system output using a suitable algorithm and reduce the mechanical parts of the old system. A conceptual design of the digital altimeter has been introduced and implemented as a virtual instrument model using a computer program so as to measure and monitor the performance of the system. Air data acquisition and display system have been designed to process the data coming from a barometric sensor and display the actual altitude information in a digital readout. In addition to that, the concept of the altitude alert system has been carefully considered to alert the pilot when reaching a maximum cruising altitude.

Keywords—digital altimeter; conventional altitude measurement system error; ISA model; conceptual design of digital altimeter, accuracy of a digital altimeter.

I. INTRODUCTION

The flight instruments are those instruments provide the aircraft pilots information's about the flight situation, enable an airplane to operate within safe and efficient boundaries. The altimeter is one of the most important of these instruments used to determine the altitude of the vehicle during flight. Knowing of altitude information for any flying vehicle is very important for all aerospace users to achieve safe and efficient flight operation by keeping the vehicles above obstacle's peak, maintain desired flying course and flying at a prescribed altitude assigned by air traffic control (ATC) to reduce the possibility of midair collision when the visibility is restricted. [1]

There are different methods were used in the aerospace field to determine the altitude of the flying object, the barometric and radio methods are two methods commonly used in the aviation field. The principle of barometric altimeter is based on a barometric method for altitude measurement, which depends mainly on the International Standard Atmosphere (ISA) model of the earth to compute the altitude of flying vehicle by sensing the variation of atmospheric pressure with the height using sensitive pressure element (sensor). Therefore the deformation of this sensor (aneroid capsules) will be proportionally to changes of the atmospheric pressure and consequently to the height of the flying vehicle, so the expansion and contraction of this capsule could be converted and translated to display the equivalent flying altitude in digital or analog read out. [2]

Due to complexity and integration of aerospace technology and applying the computer science in aviation field , the aircraft become a practical means of transportation in addition to many other sensitive applications in aerospace , therefore accurate instruments system is essential to sense and acquire data on a variety of aircraft systems during flight, thus the development of altitude measurement system (altimeter) is much needed to provide accurate flying altitude information to the pilots and other integrated computer systems during flight. So that this paper focusing deeply on analyses and design of a digital barometric altimeter system to suit this integration.

II. ALTITUDE MEASUREMENT METHODS

There are various methods for altitude determine as mentioned and discussed below, but this paper focusing on the enhancement of the barometric method for altitude measurement and design of the digital barometric altimeter.

A. Acoustic method for altitude measurement

The principle of this method based on the transmission of sound waves down to the reference surface of which the altitude will be measured, the echo of the waves will receive again by the aircraft and the time taken by the system to transmit and receive of this signal will be measured and then the altitude of the flying object can be calculated from the relation below.

$$H = \left(\frac{t}{2}\right) \times V \qquad (1)$$

H: height of the vehicle (m)
V: speed of the sound (m/s)
t: propagation time of the signal (s)

B. Acceleration method for altitude measurement

This method mainly based on the measurement of the vertical acceleration of the vehicle (aircraft) and then integrates it twice to obtain the height of the aircraft.

C. Radio method for altitude measurement

The radio altimeter is an altitude measurement system that commonly used in most aircrafts during landing to determine the height of the aircraft above a ground. The accuracy of Commercial radio altimeters is up to two feet and less at low altitude, therefore the radio altimeter is essential for a safe landing to provide the pilot with actual altitude information. The principle of this method as shown in Fig.1. is based on the measurement of time which may take by the electromagnetic wave propagating at the speed of sound to reflect back to the aircraft from such reference surface.[3]

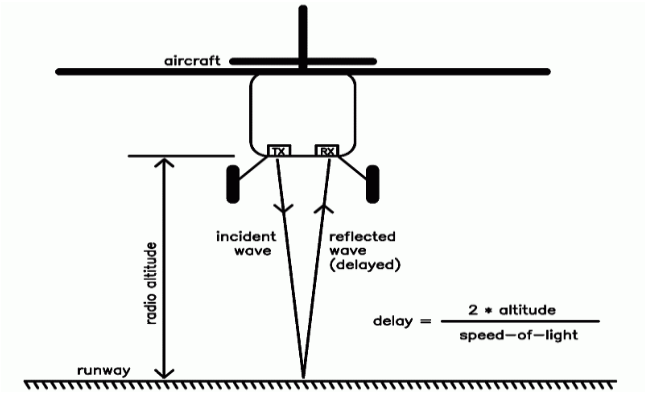

Fig.1. *radio method for altitude measurement*

The distance between the surfaces which providing the reflection and the aircraft can be calculated from the relation illustrated below.

$$H = \left(\frac{t}{2}\right) \times c \tag{2}$$

H: height of aircraft (m)

c: the speed of light (3×10^8m/s)

t: time of signal propagation (s)

D. Barometric method for altitude measurement

It's a most commonly method used in aviation field for altitude measurement, the principle of barometric altimeter is based on the of international standard atmosphere (ISA) model to calculate the flying altitude by sensing the variation of air pressure with the height by apply ISA relations as explained in equations 3 and 4.

The International Standard Atmosphere (ISA) model is a standard model for the variation of the earth's atmosphere parameters with altitude; this model has been established and accepted by ICAO to provide the aerospace users a reference values for atmospheric parameters at different altitudes, in addition to some relations for how those values were derived. The ISA model divides the atmosphere into layers, assuming that the atmospheric parameters at sea level will remain constant (pressure is 1013.25 Pa, the temperature is 15° C and temperature lapse rate is -6.5 °C/km) and continues to tabulate these parameters until 11 km above mean sea level (AMSL), as shown in Fig. 2. and Fig. 3. [4]

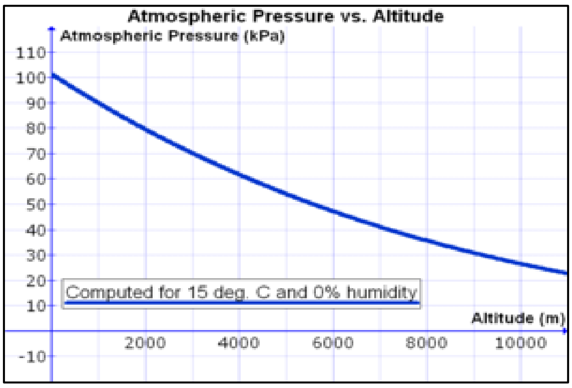

Fig.2. *Variation of atmospheric pressure with altitude*

The variation of these parameters (pressure and temperature) with altitude has been used to generate standard relation for calculate the altitude of flying objects at any height below 11km (troposphere) as shown in equation (3).[5]

$$H = \frac{T_0}{\alpha}\left[\left(\frac{P_H}{P_0}\right)^{\frac{R*(\alpha}{g}} - 1\right] \tag{3}$$

The temperature will remain constant from 11 km to 20 km and then will change with altitude as shown in Fig.3. , therefore other relation (Laplace relation) has been used to calculate the flying altitude above 11km as explained in equation (4).

$$H = 11{,}000 - R \times T_{11} \operatorname{Ln}\left(\frac{P_H}{P_{11Km}}\right) \tag{4}$$

Where:

P_0 : standard atmospheric pressure at sea level (101.325 k Pa)

T_0: standard atmospheric temperature at sea level (288.15° K)

g: the gravity acceleration at sea level (9.80665 N/m^2)

R: the universal gas constant (287.05287 m^2/ (K x s^2))

α: The vertical temperature change rate (-6.50° K/km)

P_H: Air pressure at certain flying altitude (k Pa)

H: the flying altitude (km)

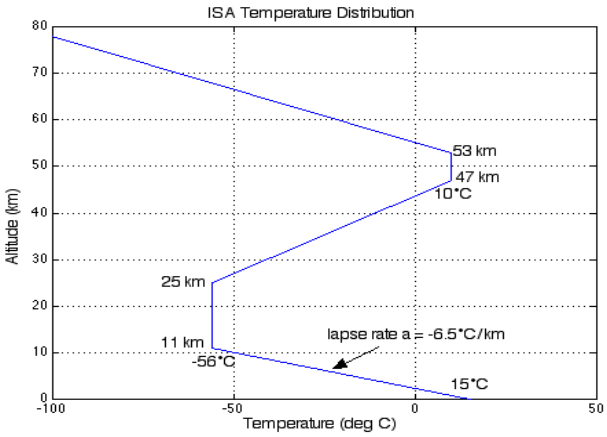

Fig.3. *Variation of atmospheric temperature with altitude*

The ISA model defines the atmospheric temperature profile as a pattern of linear Sequences as shown on fig.3, so the temperature decrease with altitude at constant rate of -6.5° c/ km up to 11km and then remain at constant value of -56°C up to 20km and continue the variation depending on the change rate in each region. This variation of atmospheric temperature described in equation (5) with variance of temperature laps rate in each layer.

$$T_h = t_O + \alpha * H \quad (5)$$

T: temperature at certain altitude
To: temperature at sea level
H: altitude
α: temperature change rate (-0.0065°C /m)

III. ERRORS SOURCE OF THE ALTIMETER

The barometric altimeter may subject to numerous sources of errors during operation. Those errors has been carefully considered, diagnosed and compensated in this design to provide the actual altitude information to the pilots and other integrated systems during flight.

A. Methodical errors (ΔH)

This error results from the method used for measuring the vehicle altitude, which is due to drift in the atmospheric parameters ($\Delta T_o, \Delta P_H, \Delta\alpha$ an ΔP_o) away from their ISA values.[6],[7] This error can be quantified and estimated for correction purposes, by using Taylor's series relations as expressed in Equation (6) below.

$$\Delta H = \sum_1^{\infty}\left(\frac{\delta^i H}{\delta {T_o}^i}\cdot\frac{\Delta {T_o}^i}{i!} + \frac{\delta^i H}{\delta\alpha^i}\cdot\frac{\Delta\alpha^i}{i!} + \frac{\delta^i H}{\delta {P^i}_H}\cdot\frac{\Delta {p_h}^i}{i!} + \frac{\delta^i H}{\delta {P^i}_o}\cdot\frac{\Delta {P^i}_o}{i!}\right) \quad (6)$$

Then it is used to compensate the deviation of the measurement system from its true value

$$H = (H_o + \Delta H) \quad (7)$$

A-1. Temperature drift

To quantify the absolute temperature errors(ΔH_{T_o} and ΔH_α) which will produce from the deviation of the atmospheric parameter at sea level (temperature,and the vertical temperature gradient) from their standard ISA values, the following expressions have been used to quantify these errors.

$$\Delta H_{T_o} = -\frac{\Delta T_o}{T_o} H \quad (8)$$

$$\Delta H_\alpha = -\frac{T_o}{\alpha^2}\left[1 + \left(1 + \frac{\alpha}{T_o}H\right)\left(Ln\left(1 + \frac{\alpha}{T_o}H\right) - 1\right)\right]\Delta\alpha \quad (9)$$

A-2. Pressure drift

To quantify absolute pressure errors ΔH_{P_H} *and* ΔH_{P_o}, the following expressions have been used

$$\Delta H_{P_H} = \left[g.\rho_o\left(1 + \frac{\alpha}{T_o}H\right)^{-\left(1+\frac{g}{R\alpha}\right)}\right]^{-1} \Delta P_H \quad (10)$$

$$\Delta H_{P_o} = -\frac{R}{g}.(T_o + \alpha H).\frac{\Delta P_o}{P_o} \quad (11)$$

B. Systematic errors

The systematical errors of the barometric altimeter are those errors caused due to the system itself, which result from manufacturing discrepancies, hysteresis, friction, inertia of moving parts and change of modulus of elasticity of pressure measuring element. These errors can be compensated by inserting bimetallic mechanical parts on the mechanism of the instrument and accomplishing regular a laboratory calibration of an altimeter. [6]

C. Dynamic errors

This error is caused due a difference in local static pressure and free stream pressure due to movement of flying object on a static atmosphere, which will increase the flow disturbance around the Pitot probe and result to error as shown on fig.4.

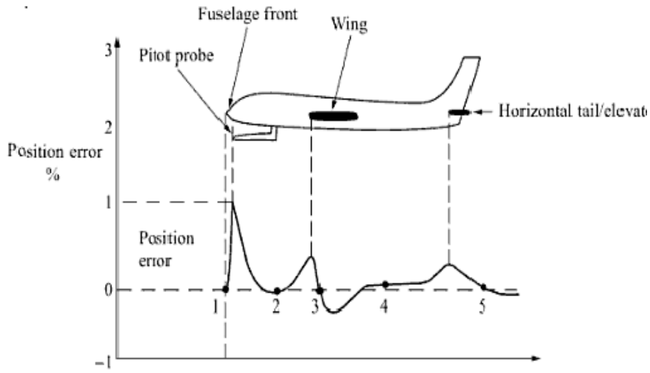

Fig.4. *Pitot static position error along the aircraft*

This error must be considered from the design stage, and can be minimized through aerodynamically shaping of the probe and locating the probe in minimum disturbance point along the aircraft [6], as illustrated in Fig. 4.

IV. DESIGN OF A DIGITAL BAROMETRIC ALTIMETER

digital barometric altimeter mainly is the same as conventional altimeter in principle of operation, such that both systems measure the vehicle altitude by detecting changes in atmospheric pressure, and convert it to equivalent altitude, but in digital altimeter uses high sensitive pressure sensing element (capsule) to achieve accurate degree of movement for given small change in atmospheric pressure, transduces the response of the sensor (expansion & contraction) into an electrical signal by using suitable pressure transducer, and then apply the conditioned electrical signal to computer system to calculate the corresponding aircraft altitude according to Equations (1) or (2) and provide the altitude information in digital read out.

The digital barometric altimeter system consists of different stages as shown in the conceptual design in Fig. 5.

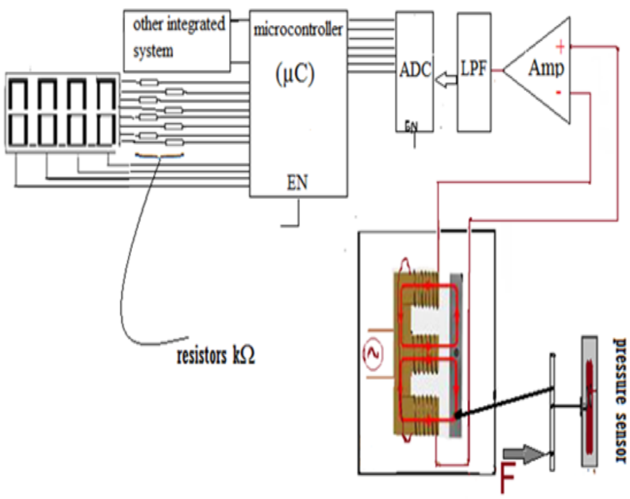

Fig.5. *Conceptual design of the digital barometric altimeter*

A. Sensing stage

A variation of the Physical variable (atmospheric pressure) with the flying altitude has to be sensed in this stage by using pressure capsules .

B. Transducer stage

The net deformation of the capsules is to be transferred to an electrical signal by using EI bars electromagnetic transducer (when I bar moves from its equilibrium position the air gaps between the two limbs will become unequal, resulting flux change at the limbs and then the induced voltages will change according to the movement of the I bar from its equilibrium and consequently to net force applied from deformation of the pressure sensing element).

C. Signal conditioning stage

The electrical signal must be conditioned and adapted (amplifying, filtering and converted to a digital signal) in this stage to suit further computing processes.

D. Measurement process stage

The conditioned signal has to be applied to the system equation to compute the equivalent altitude, compensate all expected errors and provide accurate altitude information in a digital readout. The PIC16f84 microcontroller has been used as a processor in this design to meet all specifications needed by the design Such as low power consumption, low pin count, flash program memory, RISC architecture, and other advantages.

E. Display stage

Computed altitude information has to be conditioned and translated to digital display to provide the pilot with accurate and precise altitude information in a digital readout.

F. calculation algorithm (flow chart)

The PIC16f84 has been programmed according to the flow chart described below. Therefore the processor will receive signal from the pressure transducer according to pressure variation with altitude and calculate equivalent altitude using relations described in equations (3&4)and then provide the altitude information in digital read out after compensating all expected errors may subject to the system. The concept of altitude alerting system was added to the altimeter system to provide the pilot with a message (voice / text) when the aircraft reaches selected cruising altitude by comparing the reading of altimeter and the pre-selected altitude.

F. Software model of a digital barometric altimeter

The performance and capability of the designed digital barometric altimeter system has been monitored through modeling the design using computer program (LabView) as shown on Fig.7. After running the simulation, good results have been achieved, as those are shown in Fig. 8.

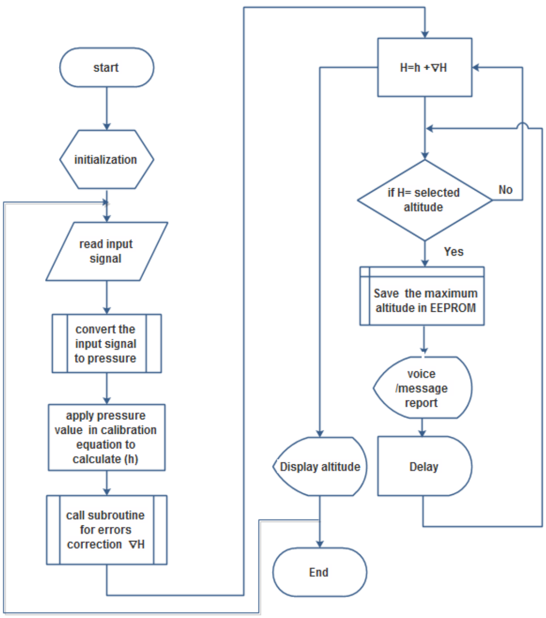

Fig.6. *Program flow chart*

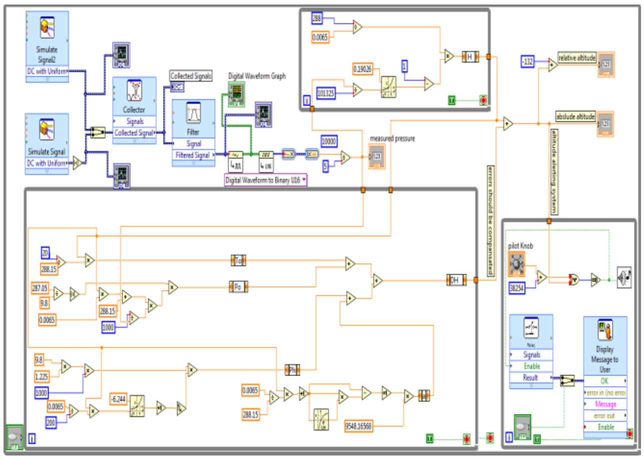

Fig.7. *Software model of a digital barometric altimeter*

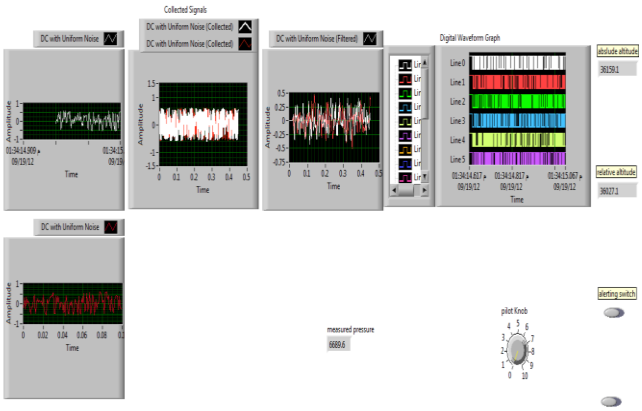

Fig.8. *simulation result of a digital barometric altimeter*

V. DVANTAGES OF THE DIGITAL ALTIMETER

1) The digital altimeter is sensitive, accurate and most of expected errors can be compensated more easily.
2) Digital display can incorporated into the system and this reduces the Pilot effort to read and absorb the data content
3) Provide the user a more accurate reading at all altitudes (more than 4 digits can be displayed to indicate the altitude information)
4) The digital altimeters suit the integration of aircraft instrument systems and share the altitude information with other integrated systems.
5) Altitude warning devices can be easily incorporated into the system.

VI. CONCLUSION

Due to the integration of the new technologies of aerospace and aircraft avionics system, the altitude information must be accurate as than ever, and to be in digital form in order to suit this integration.

An overview of Aircraft altitude measurement is presented in this paper and a good solution was proposed by designing accurate and precise a digital altitude measurement system, through deeply study and analyses of all errors subject to the system, expressed these errors in mathematical derivations for compensation purpose. The conceptual design has been implemented in a computer program to measure and monitor the performance of the designed system and the good result has been achieved.

VII. Acknowledgment

First and foremost, all the thanks and the praise for ALLAH, who created this complex world in details and diversity and gives us the health, the strength and the power to wind up this work. The authors would like to acknowledge colleagues in the Institute of Space Research and Aerospace (ISRA) for their encourage, kind support and valuable guides .

VIII. References

[1] E.H.J pallet, aircraft instruments (second edition) ,Longman publishing group 1988 (*references*)

[2] Chris Winkler and Jeff Baum, barometric pressure measurements using semiconductor sensors AN 1326 , 3/11/2006

[3] Pallet , E.H.J, aircraft instrument and integrated system(November -1-1992)

[4] Liu, H. and G. Darkow, Wind effect on measured atmospheric pressure, Journal of Atmospheric and oceanic technology 1989

[5] Liu, H. and G. Darkow, Wind effect on measured atmospheric pressure, Journal of Atmospheric and oceanic technology 1989

[6] Reilly Burke , FLIGHT INSTRUMENTS, 2005

[7] young yee erik mkey,a study of barometric altimeter errors in high latitude regions, ste 100-3 Santa Teresa, New Mexico 88008 ,1999

[8] Jan čižmár1 – miloš andrle [2], accuracy of aircraft barometric altimeters, 1996.

[9] Mike tooley, aircraft electronic and computer systems, principle operation and maintenance, Linacre House, Jordan Hill, Oxford OX2 8DP, UK 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA , First edition 2007(references)

[10] Boyes, Walt. Instrumentation Reference Book, Fourth Edition. Butterworth-Heinemann. pp. 1312 (2008)

[11] McGraw hill, making PIC microcontroller instruments and controllers, 2009