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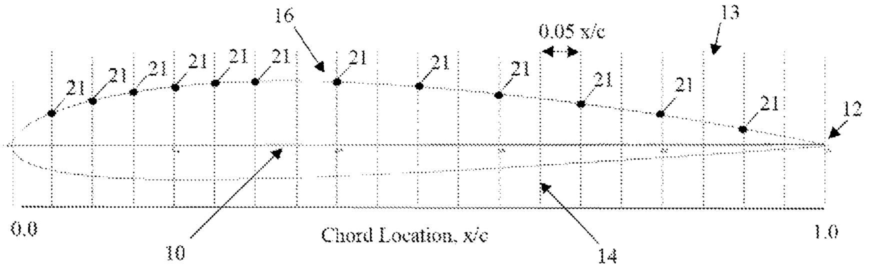

Figure 3

(57) Abstract: A method and apparatus for angle of attack (AOA) sensing requires a series of surface mounted pressure sensors (21) provided along a chord line of an airfoil (10). A processing unit (30) is operable to calculate a local pressure coefficient C_p for each sensor (21). Subsequently the processing unit (30) carries out an integration over signals indicative of local pressure along the chord line to enable the determination of a local pressure coefficient and hence the local AOA. In further embodiments, multiple sets (22) of sensors (21) are provided, each set (22) on a different chord line (21). In such embodiments, a global pressure co-efficient can also be calculated with both chordwise and spanwise integration.

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IMPROVEMENTS IN OR RELATING TO ANGLE OF ATTACK SENSING

Technical Field of the Invention

The present invention relates to angle of attack (AOA) sensing for aircraft. In particular, the present invention relates to multipoint AOA sensing.

Background to the Invention

The angle of attack (AOA) of a body is defined as the angle between a reference axis of the body and the relative fluid flow direction. Typically, where the body is an airfoil such as a wing, the reference axis is the chord line. In such cases, the vector representing the relative motion between the aircraft and the atmosphere may be used to define the relative flow direction.

Where it is possible to monitor the AOA of an aircraft, this information may be used to help control flight systems and/or to activate warning systems such as stall warning systems. In view of this utility, AOA sensors are fitted to most commercial aircraft. Recent Federal Aviation Administration (FAA) promotion of Angle of Attack (AOA) systems for stall prevention to reduce Loss of Control In-flight (LoC-I) accidents in the General Aviation sector has resulted in AOA sensors being fitted to a wide variety of general aviation aircraft.

In commercial aviation, such sensors are typically used to measure a general AOA for the aircraft. One type of commercial AOA sensor comprises a rotatable vane projecting from the aircraft body and free in use to align with the direction of local fluid flow. By sensing the relative orientation of the base of the vane to the axis of the aircraft body, a measure of the AOA can be obtained. Another type of commercial AOA sensor comprises a probe having two or more sensing pressure ports displaced from one another. The differential pressure between the ports can provide a measure of the orientation of the local fluid flow relative to the aircraft body, and hence a measure of AOA. By calibrating the output of the AOA sensors to the aircraft body orientation during a testing program, a relationship between sensor output and overall AOA can be determined. For many flight conditions, this overall AOA is adequate for determining when an aircraft is approaching the edge of its safe flight envelope. Nevertheless, such an overall AOA measure may not be adequate in certain flight conditions such as a skid and slip turn. As a result, all or significant parts of an airfoil could have an AOA indicative of a likely stall without the overall AOA measure providing such an indication. This can lead to loss of control of the aircraft.

It is therefore an object of the present invention to provide an improved method and apparatus for AOA sensing.

Summary of the Invention

According to a first aspect of the present invention there is provided a method for angle of attack (AOA) sensing, the method comprising the steps of: providing multiple pressure sensors on the surface of an airfoil along a chord line; obtaining output signals from each sensor indicative of local pressure at each sensor location; and processing the signals indicative of local pressure to determine the AOA of the airfoil, wherein the processing comprises an integration over signals indicative of local pressure along the chord line.

According to a second aspect of the present invention there is provided an angle of attack (AOA) sensing arrangement, the sensing arrangement comprising multiple pressure sensors provided on the surface of an airfoil along a chord line, each pressure sensor operable to output a signal indicative of local pressure at the sensor location; and a processing unit connected to each sensor, the processing unit operable to process the signals indicative of local pressure to determine the AOA of the airfoil, wherein the processing comprises an integration over signals indicative of local pressure along the chord line.

The present invention takes advantage of the fact that local pressure varies along a chord line of an airfoil. By measuring the variation in local pressure along the chord line, in particular the relative location of the peak pressure, the AOA can be determined. In this context, as the AOA of the airfoil increases, the location of the peak pressure moves toward the leading edge of the airfoil. In addition, the integration provides a more robust and accurate method for determining the AOA over a wide range of angles and accounts for changes in pressure along the chord which can vary significantly as the AOA changes.

The method may include the step of determining the AOA by generating a measured pressure distribution along the chord line from the sensor outputs. The method may then include the step of comparing the measured pressure distribution to one or more stored pressured distributions so as to determine the AOA. The pressure distributions may be stored in a lookup table. The step of comparing may be performed by the processing unit. The AOA may be calculated by the processing unit using the results of the comparison. The stored pressure distributions may be generated by use of a suitable theoretical model and/or by calibration testing. In one embodiment, a suitable theoretical model is a Vortex Lattice Model (VLM). In some embodiments, advanced computational fluid dynamics using Reynolds-averaged Navier-Stokes equations could be used to generate pressure distributions.

The generation of a measured pressure distribution and/or the comparison to one or more stored pressured distributions may be carried out by the processing unit. The stored pressured distributions may be stored in a data store.

The method may include the step of comparing the determined AOA to a range of safe AOA values. In the event that the determined AOA exceeds the safe range an alarm can be output. The comparison may be carried out by the processing unit. The safe range may be stored in a data store.

The alarm may be output to a connected audio and/or visual interface. The interface may be connected to the processing unit via any suitable wired or wireless connection.

Generating a measured pressure distribution may be carried out using the raw outputs of each sensor. The outputs of each sensor may be processed to determine a local pressure coefficient C_p for each sensor. The local pressure coefficients C_p may be used to generate the measured pressure distribution. This processing may be carried out by the processing unit.

The local pressure coefficient C_p may be calculated from a relation such as:

$$C_p = \frac{P - P_\infty}{\frac{1}{2} \cdot \rho_\infty V_\infty^2}$$

where P_∞ is the freestream static fluid pressure, V_∞ is the freestream dynamic fluid velocity and ρ_∞ is the freestream fluid density. The method may include the additional steps of measuring one or more of: freestream static fluid pressure P_∞, freestream dynamic fluid velocity V_∞ and/or freestream fluid density ρ_∞. In one embodiment, the sensing arrangement may comprise dedicated sensors for measuring such characteristics. In another embodiment, the sensing arrangement may be connected to external sensors for sensing such characteristics. Advantageously, the local pressure co-efficient can be easily calculated as it is derived from sensors that are already common on current aircraft.

In some embodiments, the airfoil is a wing or tail plane of an aircraft. Additionally or alternatively, the airfoil may be a fixed sensing vane of an aircraft. Such a sensing vane may project from any suitable position on the aircraft.

The sensors may be evenly spaced along the chord line. In such embodiments, the sensor spacing may be defined by a fraction of the length of the chord. In some such embodiments the sensor spacing may be say 10% of the chord length or say 5% of the chord length. In some embodiments, the sensor spacing may vary along the chord line. In such embodiments, there may be different even sensor spacings along different portions of the chord line. Alternately, the sensor spacing may be varied between each pair of sensors. In some such embodiments, the sensor spacing may be determined by reference to the airfoil shape and/or the expected pressure distribution. In such cases, the sensor spacings may vary in a non-linear fashion. In some embodiments with varied sensor spacings, the sensor spacing may be shorter in a leading portion of the chord line than in a trailing portion of the chord line. In such embodiments, the leading portion may be defined as that portion of the chord line that is closer to the leading edge of the airfoil than the trailing edge of the airfoil.

In one embodiment, the pressure sensors are only provided on the upper surface of the airfoil. In a further embodiment, the pressure sensors may only be provided on the leading portion of the airfoil. This reduces the cost and complexity as not all regions of an airfoil are required to achieve sufficient AoA sensing performance.

The sensing arrangement may comprise multiple sets of pressure sensors. Each set of pressure sensors may be provided on a different chord line. The multiple sets of pressure sensors may be provided at different chord lines of a single airfoil. In such embodiments, the method may include the step of determining a local AOA for each set of chord-wise pressure sensors. This can provide local AOA measurements at different chord lines spanwise along the airfoil. In some instances, an AOA indicative of a likely stall may vary with position along an aircraft wing. By providing multiple sets of pressure sensors, the present invention can enable the determination of potentially dangerous AOA at any monitored part of the wing.

The local AOA may be calculated from a chord pressure co-efficient. The chord pressure co-efficient may be calculated by integrating output signals indicative of local pressure from each pressure sensor along a chord line. Such output signals may be the local pressure co-efficient at each pressure sensor. A chord pressure co-efficient may be calculated for each set of pressure sensors. The chord pressure co-efficient, $C_{P_{Chord}}$, may be calculated using:

$$C_{P_{Chord}} = \int_{\frac{x}{c}=1}^{\frac{x}{c}=0} C_P \, dx$$

where c is the chord length.

The local AOA, α_{Local}, and chord pressure co-efficient may have a linear relationship. The relationship may only be linear up to a stall AOA. The local AOA may by calculated using:

$$\alpha_{Local} = \left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right] C_{P_{Chord}} + C_{PLocal_0}$$

where C_{PLocal_0} is the chord pressure co-efficient at $\alpha_{Local} = 0$ degrees. $\left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right]$ may be indicative of the gradient of the linear relationship. $\left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right]$ and/or C_{PLocal_0} may be calibrated by measuring the chord pressure co-efficient at two known local AOA values. The one or more calibration points may be at a cruise AOA and/or stall AOA. The cruise AOA may be 3 degrees. The stall AOA may be 15 degrees.

In some embodiments, the method may include the calculation of a global pressure co-efficient. The global pressure co-efficient may be calculated using output signals from multiple sets of pressure sensors. The calculation of the global pressure co-efficient may involve one or more chord-wise calculations, span-wise calculations, or similar. The calculation of the global pressure co-efficient may involve a chord-wise calculation and then a span-wise calculation. In certain embodiments, calculation of the global pressure co-efficient may involve a chord-wise integration and then a span-wise integration. In such embodiments, the global pressure co-efficient may be calculated by integrating the chord pressure co-efficient over the span of the airfoil. The global pressure co-efficient may be calculated using:

$$C_{P_{Global}} = \int_{\frac{z}{b}=1}^{\frac{z}{b}=0} \left[C_{P_{Chord}}\right] dz$$

where b is the span length. In some embodiments, the global pressure co-efficient may be calculated by a double integration of the local pressure co-efficient, C_P.

The method may include the step of approximating the lift co-efficient. The lift co-efficient may be calculated using the global pressure co-efficient. The lift co-efficient may be approximately equal to the global pressure co-efficient. Advantageously, the global pressure coefficient can be used to approximate the lift co-efficient of the airfoil. Using the mean, average, or summation of the multi-point sensor data would not produce the same approximation of the lift co-efficient as the lift co-efficient can be calculated from integrating the local pressure co-efficient or from direct lift force data. The benefit of approximating the lift co-efficient is the raw processed data is useful and meaningful, unlike current methods.

The method may include the step of calculating the AOA from the calculated global pressure co-efficient. The method may include the additional step of calibrating sensor outputs with respect to a measured AOA. The method may include the step of calibrating AOA during a flight test to determine the AOA vs global pressure co-efficient relationship for AOA sensing. The AOA and global pressure co-efficient may have a linear relationship. The linear relationship may only exist at AOA values lower than a stall AOA value. The calibration may be a two-point calibration method. One or more points used in the calibration may comprise a stall AOA and/or a cruise AOA. The stall AOA may be 15 degrees. The cruise AOA may be 3 degrees.

Advantageously, the relationship between AOA and global pressure co-efficient is linear up to the critical AOA (stall) region allowing for a simple and reliable calibration. The global AOA, α_{Global}, may be calculated using:

$$\alpha_{Global} = \left[\frac{\Delta\alpha_{Body}}{\Delta C_{P_{Global}}}\right] C_{P_{Global}} + C_{PGlobal_0}$$

where $C_{PGlobal_0}$ is the global pressure co-efficient at an AOA = 0 degrees and α_{Body} is the AOA of the aircraft longitudinal axis or fuselage. $\left[\frac{\Delta\alpha_{Body}}{\Delta C_{P_{Global}}}\right]$ may be indicative of the gradient of the linear relationship between the AOA and global pressure co-efficient. $\Delta\alpha_{Body}$ and $\Delta C_{P_{Global}}$ may be calculated by measuring the respective changes in α_{Body} and $C_{P_{Global}}$ between the calibration points.

By calculating the global pressure co-efficient, the method provides a more robust AOA measurement than traditional methods by accounting for the effect of span-wise variations in pressure and AOA on the airfoil. The method therefore accounts for local AOA variations that would otherwise be ignored by a traditional single body AOA measurement, which would measure only α_{Body}. In addition, the method allows for accurate measurements at higher AOA than traditional methods, as these can be more susceptible to errors due to span-wise variations in pressure.

Additionally or alternatively, the multiple sets of sensors may be provided on different airfoils. This can provide local AOA measurements for different airfoils of an aircraft. The present invention is thus capable of determining a potentially dangerous AOA on a single wing of an aircraft.

Additionally, the sensing arrangement may be connected to one or more display interfaces. The display interfaces may be operable to display the calculated AOA. The sensing arrangement may be operable to compare the calculated AOA to a range of safe AOA values. The sensing arrangement may be connected to one or more alarm outputs. The alarm outputs may output alarms by any one or more of: visual; audible; haptic; tactile or similar means. The display interfaces may be operable to output alarms. Alarms may be output if the calculated AOA is outside the range of safe values.

According to a third aspect of the present invention, there is provided an aircraft fitted with an angle of attack (AOA) sensing arrangement according to the second aspect of the present invention or an angle of attack (AOA) sensing arrangement operable according to the method of the first aspect of the present invention.

The aircraft of the third aspect of the present invention may incorporate any or all features of the first or second aspects of the present invention as required or as desired.

The aircraft may be provided with a flight management system (FMS) operable to communicate with the AOA sensing arrangement. The FMS may receive signals from the AOA sensing arrangement indicative of local pressure at each sensor location. The FMS may be operable to determine any one or more of: the chord pressure co-efficient; the local AOA; the global pressure co-efficient; the global AOA; the lift co-efficient.

The FMS may be operable to compare the current AOA and/or lift co-efficient to a range of safe values for the AOA and/or lift co-efficient respectively. If the AOA and/or lift co-efficient is not in the range of safe values, the FMS may output an alarm. The FMS may output an alarm using any suitable sensory means. Such sensory means may be any one or more of: visual; audible; haptic; tactile or similar means.

The FMS may perform local AOA analysis. The local AOA analysis may be performed using the chord pressure co-efficient. The FMS may calculate a local AOA for each set of chord-wise pressure sensors. The FMS may calculate differences between the local AOA at different span-wise locations on an airfoil. The FMS may compare these differences to expected differences or a range of safe difference values. The FMS may compare the measured local AOA to a range of safe local AOA values. The local AOA analysis results may provide improved stall warnings. The stall warnings may be in relation to common loss of control in-flight (LOC-I) scenarios. Stall warnings may be provided during asymmetric flight conditions. Stall warnings may be output by any suitable sensory means. Such sensory means may be any one or more of: visual; audible; haptic; tactile or similar means. This kind of analysis is not possible for a human pilot to perform due to the complexity of the calculations required.

The local AOA analysis affords the pilot with more complete information about the true state of the aircraft.

The FMS may interface with other aircraft systems and sensors. The FMS may interface with an aircraft automatic flight control system. The FMS may be operable to provide the automatic flight control system with signals indicative of any one or more of: the global angle of attack; the local angle of attack; the lift co-efficient; or the like. The automatic flight control system may be operable to use signals received from the FMS to provide control signals to aircraft surface control actuators. Thus, the automatic flight control system is able to use more reliable and accurate AOA measurements and therefore the present invention increases the safety and reliability of automatic flight control systems.

According to a fourth aspect of the present invention there is provided a flight management system (FMS) for an aircraft, the FMS in communication with and operable to respond to either: an angle of attack (AOA) sensing arrangement operable according to the first aspect of the present invention; or an angle of attack (AOA) sensing arrangement according to the second aspect of the present invention.

The FMS may incorporate any or all features of the first, second or third aspects of the present invention as required or as desired.

Detailed Description of the Invention

In order that the invention may be more clearly understood one or more embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1	is a schematic illustration of an airfoil defining the angle of attack (AOA) and chord line;
Figure 2	is a schematic illustration illustrating variation in surface pressure coefficient for the airfoil of figure 1 with respect to position along a chord line for a particular AOA;
Figure 3	is a schematic illustration of the location of sensors for use in an AOA sensing arrangement of the present invention;

Figure 4	is a schematic block diagram of a sensing arrangement according to some embodiments of the present invention;
Figure 5	is a series of experimental results illustrating the conformity between predicted pressure coefficient and pressure coefficient calculated from the output of a plurality of pressures sensors in a sensing arrangement according to some embodiments of the present invention at seven different AOAs;
Figure 6	is a series of experimental results illustrating the conformity between predicted pressure coefficient and pressure coefficient calculated from the output of a plurality of pressures sensors in a sensing arrangement according to some embodiments of the present invention at different AOAs and air speeds for six different sensor locations;
Figure 7	is a series of experimental results showing the chord pressure co-efficient against AOA for chords at different span-wise locations on an airfoil; and
Figure 8	is the data in figure 7 integrated span-wise to show the final global pressure co-efficient against AOA for an airfoil.
Figure 9	is a schematic of an aircraft according to an embodiment of the third aspect of the present invention.

Turning now to figure 1, an airfoil 10, for example a wing of an aircraft, is illustrated in cross-section. In the present example, the airfoil 10 is of the common NACA 2412 profile. The airfoil has a leading edge 11, a trailing edge 12, an upper surface 13 and a lower surface 14. A chord line 15 is defined as the axis between the leading edge 11 and trailing edge 12 perpendicular to the span of the airfoil 10.

The angle of attack (AOA) of the airfoil 10 is defined as the angle, α, between chord line 15 and the relative fluid flow direction R.

In the example where the airfoil 10 is a wing of a fixed wing aircraft, during controlled flight operation, the leading edge 11 of airfoil 10 faces in the direction of travel. The aerodynamic properties of the airfoil 10 depend upon the orientation of the airfoil 10 and the velocity of the airflow. Of particular importance is the angle of attack (AOA), defined as the angle, α, between chord line 15 and the relative fluid flow direction R.

Turning to figure 2, this provides an illustration of the variation in surface pressure coefficient for each location along the upper surface 13 and lower surface 14 of airfoil 10. In this example, the pressure distribution is calculated by use of the Vortex Lattice Method (VLM) for the NACA 2412 airfoil at and AOA of 4^{o} and a Reynolds number of $1.7x10^{6}$. In this context, location along each surface 13, 14 is defined in terms of a fraction (x/c) of a chord length (c) from the leading edge 11 of the airfoil. as can be seen, the surface pressure coefficient varies with respect to location for each surface 13, 14.

The location distribution of the pressure coefficient on each surface 13, 14 varies as the AOA varies. Accordingly, by measuring surface pressure by a series of surface mounted pressure sensors 21 provided along a chord line of the airfoil 10, AOA can be measured. The pressure sensors 21 may be of any suitable form. In particular, they may be MEMS type pressure sensors. These sensors are relatively inexpensive, low profile and robust. As such AOA measurement requiring multiple such sensors is feasible and cost effective. One possible example of a suitable MEMS pressure sensor is the BMP280 sensor supplied by BOSCH.

Figure 3 illustrates how the pressure sensors 21 may be provided with respect to chord line 15. In this example, pressure sensors 21 are provided only on the upper surface 13 of the airfoil 10, although the skilled man will appreciate that sensors 21 could additionally or alternatively be provided on the lower surface 14. Sensors mounted on the upper surface 13 are preferable as the variation in surface pressure distribution at different AOA is greater for the upper surface 13.

Whilst the spacing of sensors 21 may be substantially equal along the chord, in the example of figure 3, sensors 21 are spaced more closely in the leading portion 16 of the airfoil 10, the leading portion 16 comprising that portion of the chord line that is closer to the leading edge 11 than the trailing edge 12. In the example of figure 3, the speaking of sensors 21 in the leading portion 16 is at 0.05x/c (5% of chord length) whereas the remaining sensors are spaced at 0.1x/cc (10% chord length). The reduced sensors spacing in the leading portion 16 is due to the greater variation in surface pressure distribution at different AOA for the leading portion 16 than for other portions of the airfoil 10. Indeed, it would be possible to implement the invention using only pressure sensors 21 mounted on the leading portion 16 of the airfoil 10 or indeed only on the upper surface of the leading portion 16. The skilled man will also appreciate that the sensor spacing need not conform to the specific examples described above. In particular, the sensor spacing may vary in a non-linear fashion determined by the airfoil shape and/or expected pressure distribution, so as to optimise the potential fordetecting AOA variation.

Turning now to figure 4a, a schematic block diagram of an AOA sensing arrangement 100 is shown. In figure 4a, individual pressure sensors 21 together comprise a set 22 of pressure sensors provided on a single chord of airfoil 10. The outputs of the set of sensors 22 are fed to a processing unit 30. The processing unit is operable to process the sensor outputs so as to determine the pressure distribution along the chord and hence the AOA of the airfoil.

In order that the AOA determination can take account of other fluid characteristics, the processing unit may additionally be connected to a freestream static pressure sensor 27, a free stream dynamic velocity sensor 28 and a freestream density sensor 29. Whilst the sensors 27-29 may be dedicated sensors for the present arrangement 100, the skilled man will appreciate that where such sensors are already fitted to an aircraft, these could be used instead.

In a preferred embodiment, the processing unit 30 is operable to calculate a local pressure coefficient $C_p$for each sensor 21. Typically, this could be calculated from the output pressure P detected by each sensor 21 by the following relation:

$$C_p = \frac{P - P_\infty}{\frac{1}{2} \cdot \rho_\infty V_\infty^2}$$

where P_∞ is the freestream static fluid pressure, V_∞ is the freestream dynamic fluid velocity and ρ_∞ is the freestream fluid density.

The resultant pressure coefficient distribution can then be compared against stored pressure distributions to determine the AOA of the airfoil 10 at the particular chord. The stored pressure distributions may be generated from a suitable model such as VLM discussed above and/or from calibration testing.

The output of the processing unit 30 can pass to an interface 40. The interface 40 can provide a visual and/or audio indication of the AOA to a user, such as a pilot. Additionally or alternatively, the interface 40 can pass AOA information directly to other aircraft systems for use in generating alarms and/or controlling the aircraft.

The skilled man will appreciate that the present invention allows for multiple sets 22 of sensors 21. Figure 4b thus illustrates schematically how such an arrangement 101 can be embodied. In this embodiment 101, the pressure outputs of each sensor set 22 are processed independently. The resultant output is an independent AOA measurement for each set 22. This can allow an aircraft to monitor independently the local AOA for different portions of an airfoil and/or for different airfoils.

The potential effectiveness of some embodiments of the present invention in respect to measuring AOA is illustrated in figures 5 and 6.

Turning to figure 5, an NACA2412 airfoil model 10 was fitted with BMP280 pressure transducers 21 for sensing local pressure between 0.05 x/c and 0.9 x/c. the resultant sensor outputs were processed to determine local pressure co-efficients as described above. Subsequently, the local pressure co-efficient distributions were plotted alongside the theoretical calculation of such distributions generated using VLM. The testing took place at seven different AOAs 0° (figure 5a), 5° (figure 5b), 10° (figure 5c), 12.5° (figure 5d), 15° (figure 5e), 17.5° (figure 5f), 20° (figure 5g). the tests took place at a maximum Mach of 0.127 (42 m/s) and a resultant Reynolds number (Re) of 2.39×10^6.

As can be seen from reviewing figure 5, there is broad agreement between the experimental data and the theory. Accordingly, AOA measurement using the arrangement and method of this embodiment of the present invention is feasible.

Turning now to figure 6, this provides illustration that the approach is feasible at a range of different airspeed and hence Re values. In this example, the testing carried out in respect of figure 5 was repeated using an airspeed of 28m/s and hence a Re of 1.59×10^6. More specifically, figures 6a-6f illustrate the correspondence between the theoretically calculated pressure coefficient values and measured values for a series of sensor locations namely x/c = 0.05 (figure 6a), x/c = 0.10 (figure 6b), x/c = 0.15 (figure 6c), x/c = 0.20 (figure 6d), x/c = 0.25 (figure 6e), and x/c = 0.30 (figure 6f).

Turning now to figures 7 and 8, data from multiple sets of sensors 22 arranged on different chord lines of an airfoil 10 are combined to calculate the AOA for the airfoil. This leads to a more robust and accurate measurement of the AOA and facilitates measurements at higher AOA than traditional methods. In some embodiments, the calculation of the AOA is a multi-step process involving a chord-wise and then a span-wise calculation. The processing unit 30 can provide this functionality. In certain embodiments, the AOA sensing arrangement 100 required is similar to that shown in figure 4b.

In these embodiments, the AOA is determined by first calculating a global pressure co-efficient. To calculate the global pressure co-efficient, data from each sensor 21 in a set of sensors 22 is integrated along the chord line to calculate a chord pressure co-efficient for each set of sensors 22. Figure 7 shows the calculated chord pressure co-efficient against AOA for four different chord lines on an airfoil 10. The chord pressure co-efficients in figure 7 were calculated from experimental pressure measurements along four chord lines of a NACA 2412 airfoil at AOA from 0 ° to 20 ° and an airspeed of 40 m/s. In such embodiments, the chord pressure co-efficient, $C_{P_{Chord}}$, is given by:

$$C_{P_{Chord}} = \int_{\frac{x}{c}=1}^{\frac{x}{c}=0} C_P \, dx$$

where c is the chord length. The spacing between each chord line is 20% of the span length. This demonstrates the variation in the measured chord pressure co-efficient across the span of the airfoil 10, which can lead to erroneous measurements if a single chord line is used in isolation. This effect is especially pronounced at high AOA above 16 °.

The chord pressure co-efficient from each chord line is then integrated across the span of the airfoil 10 to generate the final global pressure co-efficient. In this embodiment, the global pressure co-efficient, $C_{P_{Global}}$, is given by:

$$C_{P_{Global}} = \int_{\frac{z}{b}=1}^{\frac{z}{b}=0} \left[C_{P_{Chord}}\right] dz$$

where b is the span length. The global pressure co-efficient against AOA for the airfoil 10 is shown in figure 8. As shown in figure 8, the global pressure co-efficient provides a more robust measure of the AOA and facilitates accurate measurements even at high AOA that are not accessible to traditional measurement systems. The global pressure co-efficient can also be calculated with a double integration, where the formula for the chord pressure co-efficient is substituted into the above formula for the global pressure co-efficient.

The AOA can be calculated using the global pressure co-efficient. The global AOA, α_{Global}, is then given by the following formula:

$$\alpha_{Global} = \left[\frac{\Delta\alpha_{Body}}{\Delta C_{P_{Global}}}\right] C_{P_{Global}} + C_{PGlobal_0}$$

where $C_{PGlobal_0}$ is the global pressure co-efficient at an AOA = 0 degrees and α_{Body} is the AOA of the aircraft longitudinal axis. As shown in the above formula and Figure 8, there is a linear relationship between the AOA and global pressure co-efficient. $\left[\frac{\Delta\alpha_{Body}}{\Delta C_{P_{Global}}}\right]$ is a constant indicative of the gradient of the linear relationship. To find $\left[\frac{\Delta\alpha_{Body}}{\Delta C_{P_{Global}}}\right]$ and $C_{PGlobal_0}$ a two point calibration is used. In such a calibration, the global pressure co-efficient is measured at two known AOA values. $\Delta\alpha_{Body}$ and $\Delta C_{P_{Global}}$ are then calculated using the respective change in α_{Body} and $C_{P_{Global}}$ between the two calibration points. In some embodiments, the global pressure co-efficient can also be used to calculate the lift co-efficient of the airfoil. The lift co-efficient is approximately equal to the global pressure co-efficient.

In some embodiments, the chord pressure co-efficient is used to calculate a local AOA. There is a linear relationship between the local AOA, α_{Local}, and chord pressure co-efficient. The local AOA can be calculated using:

$$\alpha_{Local} = \left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right] C_{P_{Chord}} + C_{PLocal_0}$$

where $C_{P_{Local_0}}$ is the chord pressure co-efficient at $\alpha_{Local} = 0$ degrees. $\left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right]$ is indicative of the gradient of the linear relationship. $\left[\frac{\Delta\alpha_{Local}}{\Delta C_{P_{Chord}}}\right]$ and/or $C_{P_{Local_0}}$ are calculated by measuring the chord pressure co-efficient at two known local AOA values. The two local AOA values are a cruise AOA and a stall AOA. The cruise AOA is 3 degrees, and the stall AOA is 15 degrees.

Turning now to Figure 9, an aircraft 200 is provided with AOA sensing arrangements 100 according to an embodiment of the second aspect of the present invention on each wing 201 of the aircraft 200. Although only two AOA sensing arrangements 100 are shown, the skilled man will appreciate that any number could be provided on any and all suitable aircraft surfaces, such as on the tail of the aircraft or dedicated sensing vanes. As shown above and in Figure 4b, each AOA sensing arrangement 100 comprises a processing unit and sets of pressure sensors (neither shown in Figure 9). As described previously, the processing unit is operable to receive signals indicative of local pressure from each pressure sensor and then calculate the AOA of the wing from these signals as described above. In these calculations, the processing unit also uses information provided by a freestream static pressure sensor, freestream dynamic velocity sensor and freestream density sensor (none shown in Figure 9).

In this embodiment, the aircraft 200 also comprises a flight management system (FMS) 50 operable to communicate with: the AOA sensing arrangements; one or more display interfaces 51; and one or more alarm outputs 52. The display interfaces 51 may be provided in the cockpit of the aircraft 200. The alarm outputs are operable to output alarms by any suitable means, for example audible, visual or tactile alarms can be output.

In addition, in this embodiment, the FMS 50 is operable to receive the current AOA from each AOA sensing arrangement 100. The display interfaces 51 can then display the calculated AOA. In addition, the FMS 50 compares the current AOA to a range of safe values for the AOA. If the AOA is not in the range of safe values, the FMS 50 may output an alarm. The FMS 50 may output an alarm using the display interfaces 51 and/or alarm outputs 52.

In this embodiment, the FMS 50 also performs local AOA analysis. During local AOA analysis, the FMS 50 receives the chord pressure co-efficient for each set of pressure sensors 22 from the processing unit 30 of each AOA sensing arrangement 100. The FMS 50 then calculates a local AOA for each set of pressure sensors 22. The FMS 50 can then calculate differences between the local AOA at different span-wise locations on an airfoil and compare these differences to expected differences or a range of safe difference values. The FMS 50 may also compare the measured local AOA to a range of safe local AOA values. The FMS 50 uses the results of the local AOA analysis to provide improved stall warnings. Such stall warnings are provided in relation to common loss of control in-flight (LOC-I) scenarios and during asymmetric flight conditions. In some embodiments, stall warnings are output by the FMS 50 via the display interfaces 51 and/or alarm outputs 52.

In some embodiments, the FMS 50 is also operable to calculate the lift co-efficient of the wing 201. The lift co-efficient can be calculated using the global pressure co-efficient as described previously.

In some embodiments, the aircraft also includes an automatic flight control system 60. Automatic flight control systems are also known as autopilots and can control the flight of the aircraft. The automatic flight control system 60 is operable to send control signals to one or more surface control actuators (not shown). The surface control actuators actuate and move surface elements of the aircraft to control the flight of the aircraft. Such surface elements include: the aircrafts wings, winglets, aileron, flaps and slats; the aircraft tail, rudder, elevator and vertical stabiliser; and the like. In some such embodiments, the FMS 50 is be operable to provide the automatic flight control system 60 with signals indicative of the AOA and/or the lift co-efficient. The automatic flight control system 60 can then use the AOA and/or lift co-efficient received from the FMS to provide control signals to the surface control actuators 61.

The one or more embodiments are described above by way of example only. Many variations are possible without departing from the scope of protection afforded by the appended claims.

CLAIMS

1. A method for angle of attack (AOA) sensing, the method comprising the steps of: providing multiple pressure sensors on the surface of an airfoil along a chord line; obtaining output signals from each sensor indicative of local pressure at each sensor location; processing the signals indicative of local pressure to determine the AOA of the airfoil, wherein the processing comprises an integration over signals indicative of local pressure along the chord line.

2. A method as claimed in claim 1 wherein there are multiple sets of pressure sensors, each set of pressure sensors provided on a different chord line.

3. A method as claimed in claim 2 wherein the method includes the step of calculating a chord pressure co-efficient for each set of chord-wise pressure sensors.

4. A method as claimed in claim 3 wherein the method includes the step of integrating the chord pressure co-efficient span-wise across the airfoil to calculate a global pressure co-efficient.

5. A method as claimed in claim 4 wherein the method includes the step of using the global pressure co-efficient to determine the AOA.

6. A method as claimed in any of claims 2 to 5 wherein the method includes the step of determining the local AOA for each set of chord-wise pressure sensors.

7. A method as claimed in claim 6 wherein the local AOA is used to provide warnings for the aircraft in asymmetric flight conditions.

8. A method as claimed in any preceding claim wherein the signals indicative of local pressure are processed to determine a local pressure coefficient C_p for each sensor and the local pressure coefficients C_p are used to calculate the AOA.

9. A method as claimed in claim 8 wherein the pressure coefficient C_p is calculated from:

$$C_p = \frac{P - P_\infty}{\frac{1}{2} \cdot \rho_\infty V_\infty^2}$$

where P_∞ is the freestream static fluid pressure, V_∞ is the freestream dynamic fluid velocity and ρ_∞ is the freestream fluid density.

10. A method as claimed in any preceding claim wherein the method includes the additional steps of measuring one or more of: freestream static fluid pressure P_∞, freestream dynamic fluid velocity V_∞ and/or freestream fluid density ρ_∞.

11. A method as claimed in any preceding claim wherein the method includes the additional step of calibrating the calculated AOA with respect to a measured AOA.

12. An improved angle of attack (AOA) sensing arrangement, the sensing arrangement comprising multiple pressure sensors provided on the surface of an airfoil along a chord line, each pressure sensor operable to output a signal indicative of local pressure at the sensor location; and a processing unit connected to each sensor, the processing unit operable to process the signals indicative of local pressure to determine the AOA of the airfoil, wherein the processing comprises an integration over signals indicative of local pressure along the chord line.

13. A sensing arrangement as claimed in claim 12 wherein the processing unit is operable to process the outputs of each sensor to determine a local pressure coefficient C_p for each sensor and the local pressure coefficients C_p are used to determine the AOA.

14. A sensing arrangement as claimed in claim 12 or 13 wherein the sensing arrangement further comprises sensors operable to measure any one or more of: freestream static fluid pressure P_∞, freestream dynamic fluid velocity V_∞ and/or freestream fluid density ρ_∞.

15. A sensing arrangement as claimed in any one of claims 12 to 14 wherein the pressure sensors are evenly spaced along the chord line.

16. A sensing arrangement as claimed in any one of claims 12 to 15 wherein there are different even sensor spacings along different portions of the chord line.

17. A sensing arrangement as claimed in any one of claims 12 to 16 wherein the pressure sensors are only provided on the upper surface of the airfoil.

18. A sensing arrangement as claimed in any one of claims 12 to 17 wherein the pressure sensors are only provided on the leading portion of the airfoil.

19. A sensing arrangement as claimed in any one of claims 12 to 18 wherein the sensing arrangement comprises multiple sets of pressure sensors, each set of pressure sensors provided on a different chord line.

20. A sensing arrangement as claimed in claim 19 wherein the multiple sets of pressure sensors are provided at different chord lines of a single airfoil.

21. A sensing arrangement as claimed in claim 19 or 20 wherein a chord pressure co-efficient is calculated for each set of chord-wise pressure sensors.

22. A sensing arrangement as claimed in claim 21 wherein the chord pressure co-efficient is integrated span-wise across the airfoil.

23. A method as claimed in any of claims 19 to 22 wherein a local AOA is determined for each set of pressure sensors.

24. A sensing arrangement as claimed in any of claims 19 to 23 wherein the multiple sets of sensors are provided on different airfoils.

25. An aircraft fitted with an angle of attack (AOA) sensing arrangement according to any one of claims 12 to 24 or an angle of attack (AOA) sensing arrangement operable according to the method of any one of claims 1 to 11.

26. A flight management system for an aircraft according to claim 25, wherein the flight management system is operable to communicate with the AOA sensing arrangement and respond to outputs from the AOA sensing arrangement.

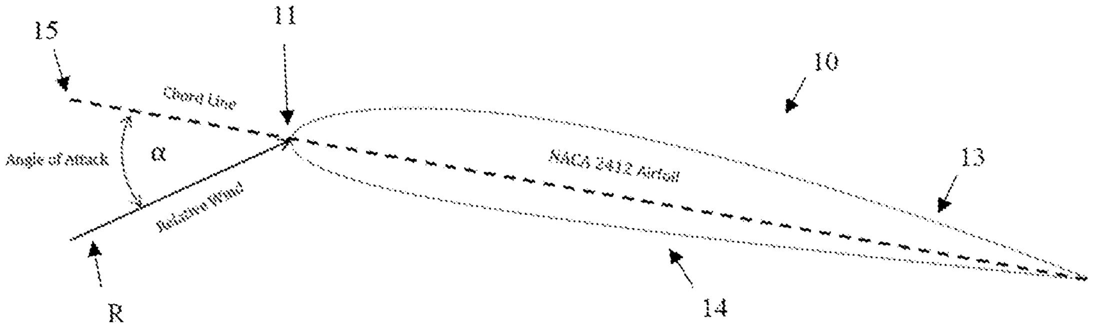


Figure 1

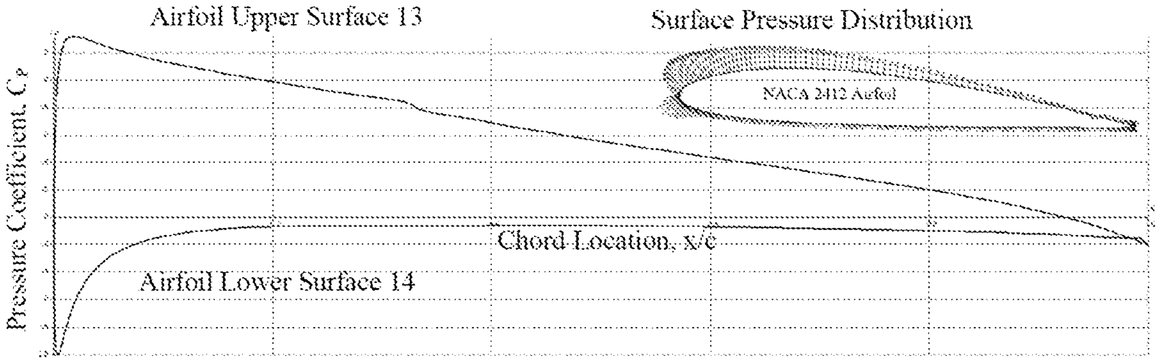


Figure 2

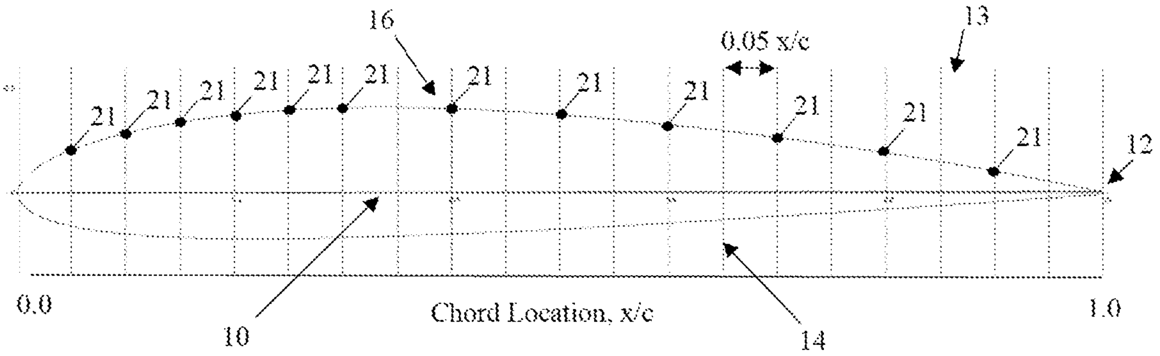


Figure 3

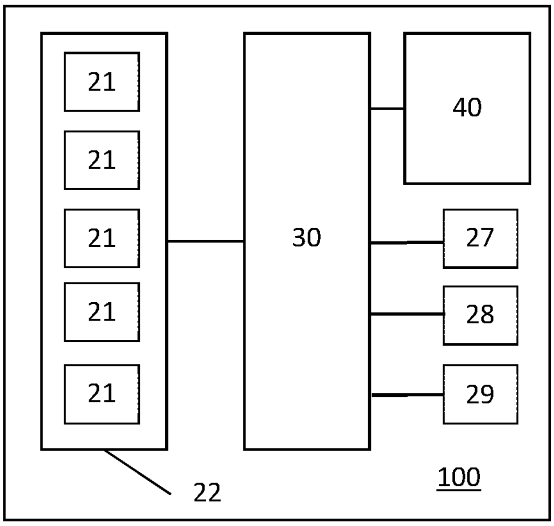


Figure 4a

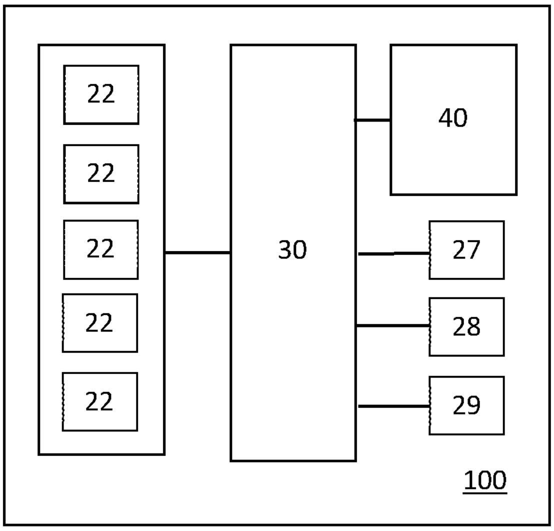
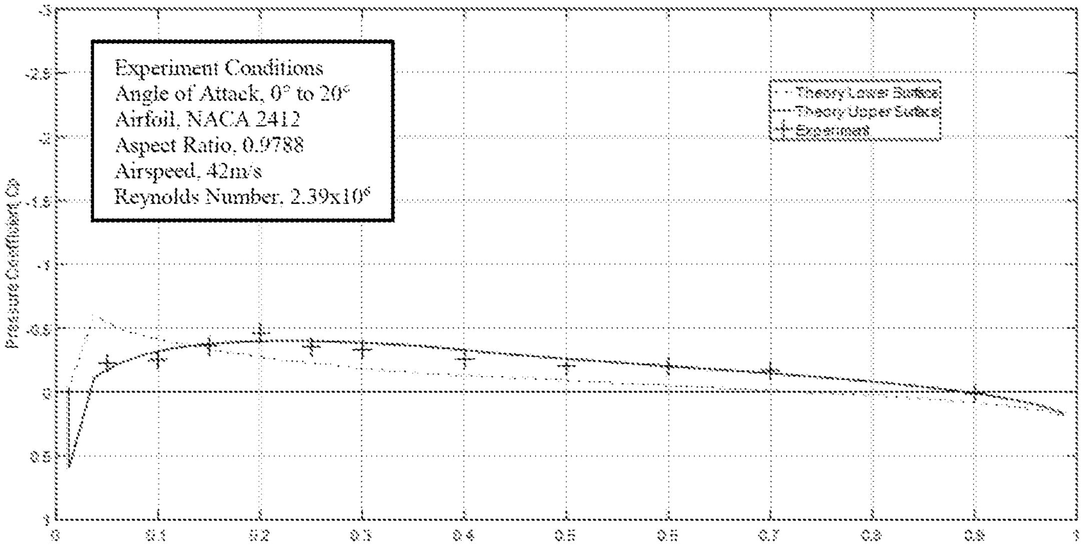
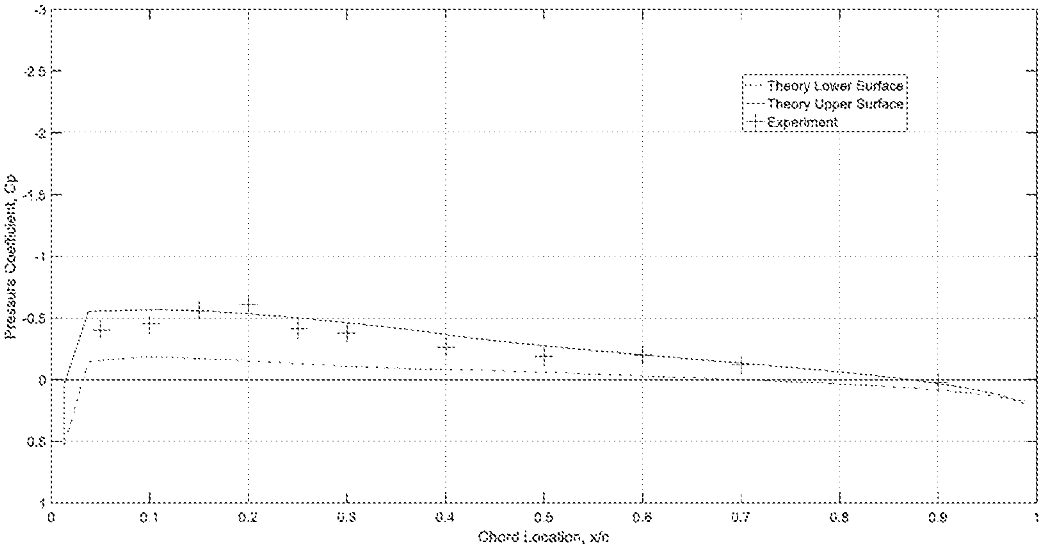


Figure 4b

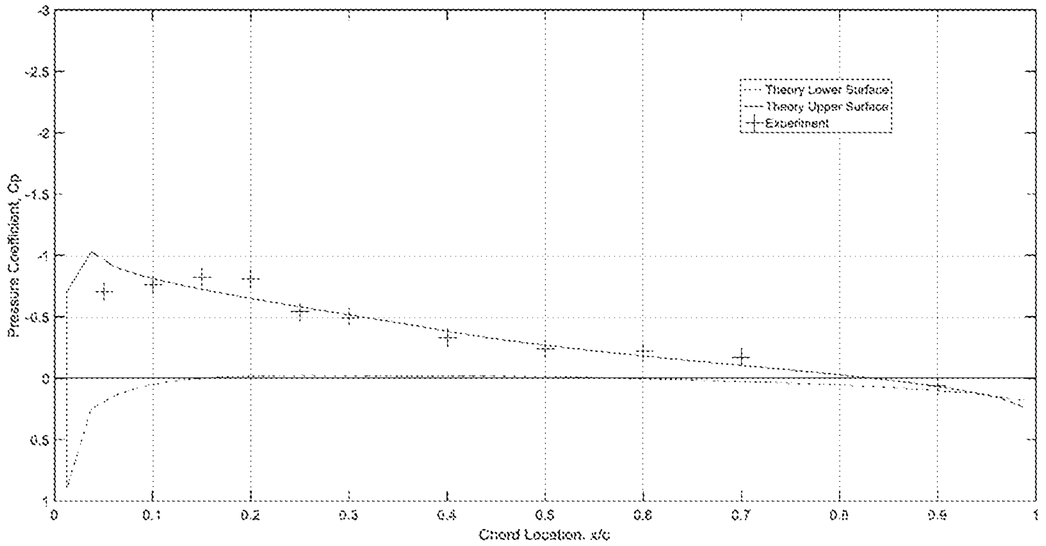


a) Angle of Attack = 0°

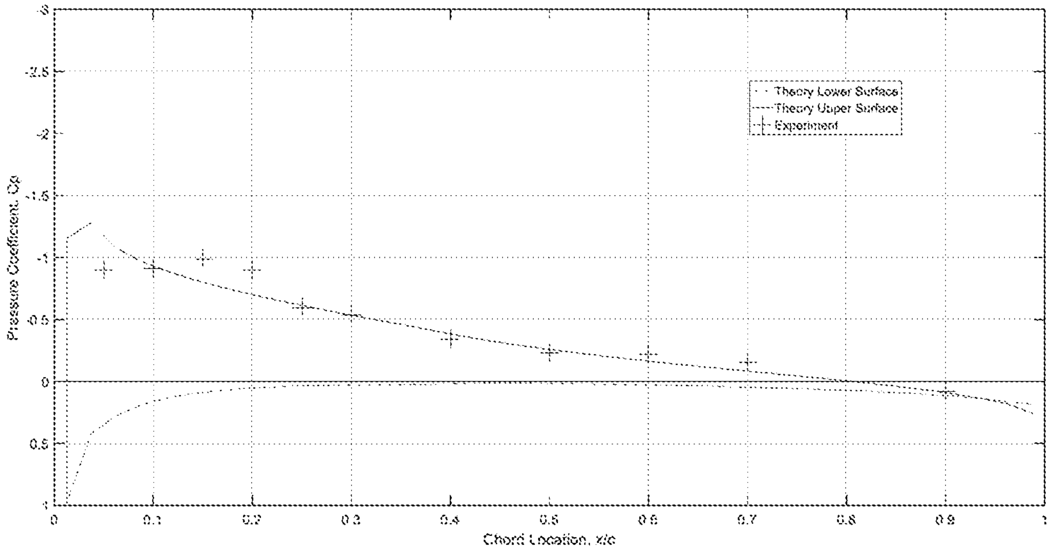
Figure 5



b) Angle of Attack = 5°

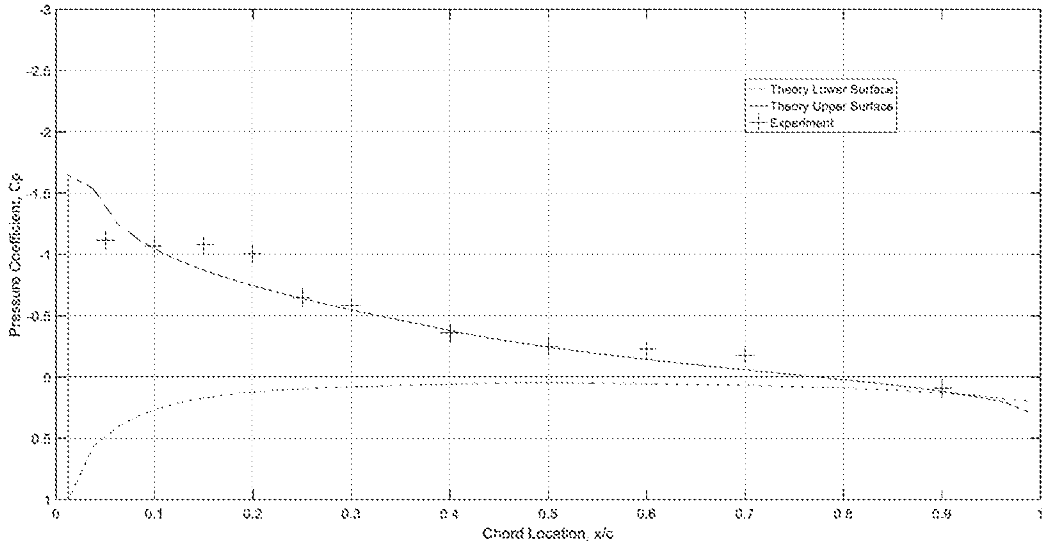


c) Angle of Attack = 10°

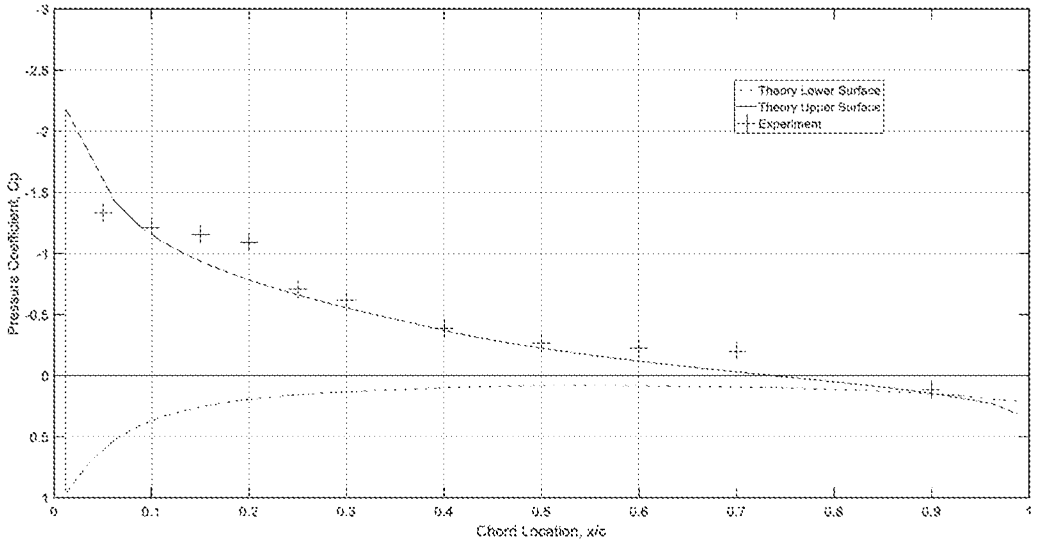


d) Angle of Attack = 12.5°

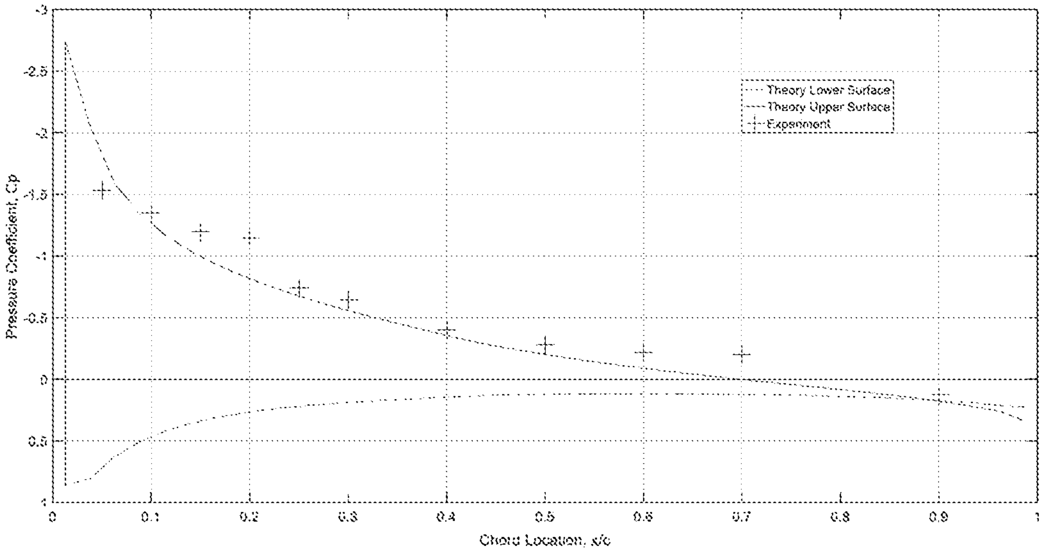
Figure 5



e) Angle of Attack = 15°

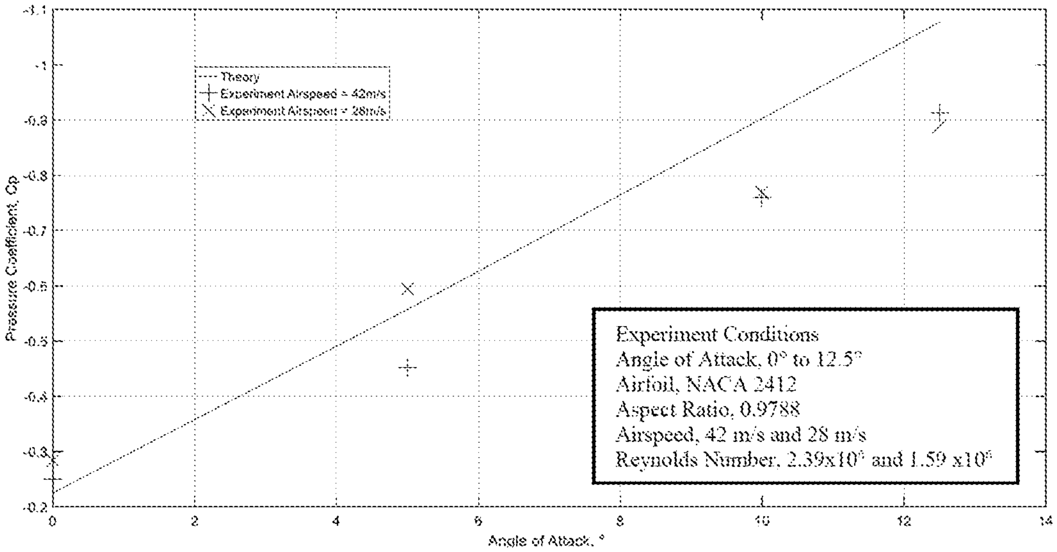


f) Angle of Attack = 17.5°

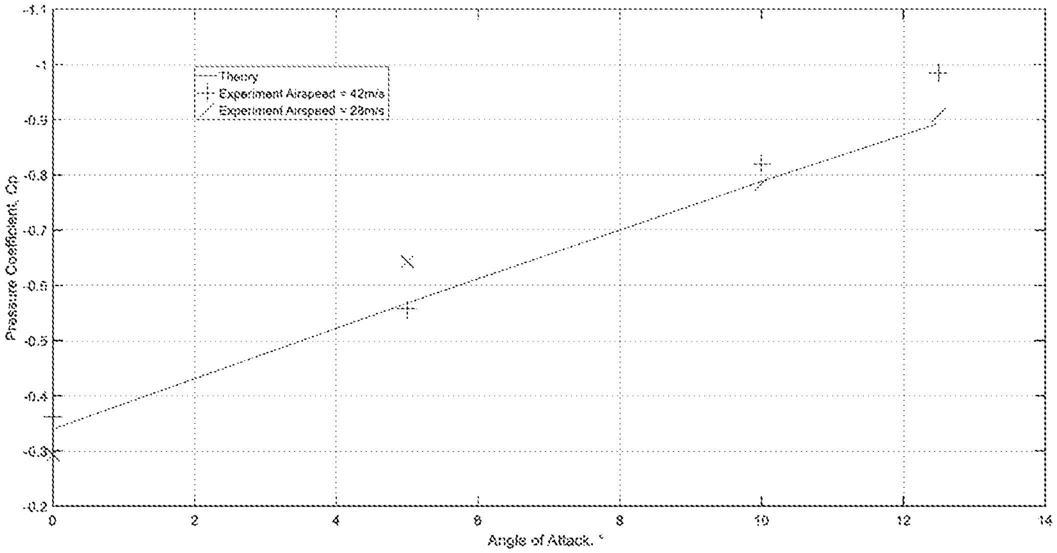


g) Angle of Attack = 20°

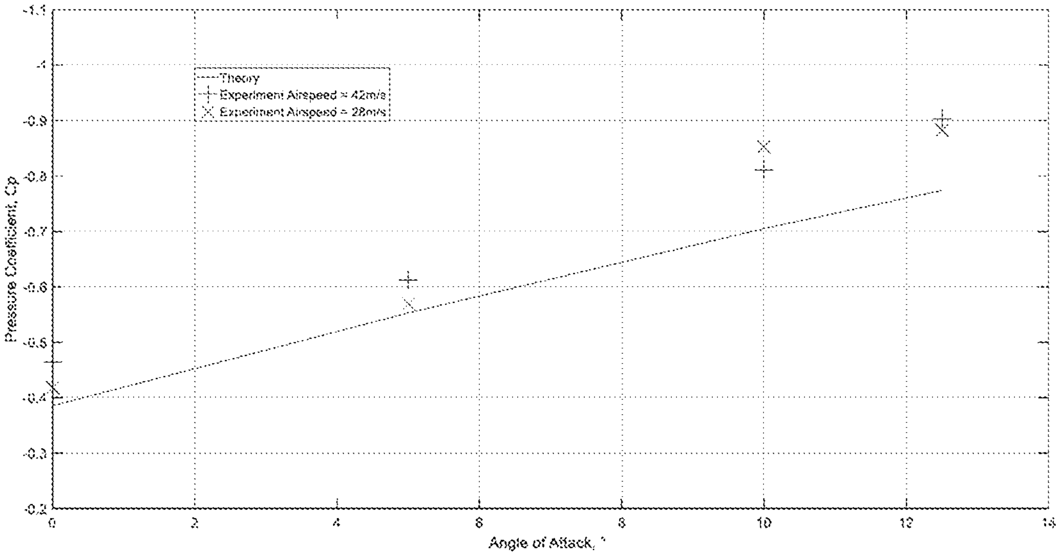
Figure 5



a) Chord Location, x/c = 0.05

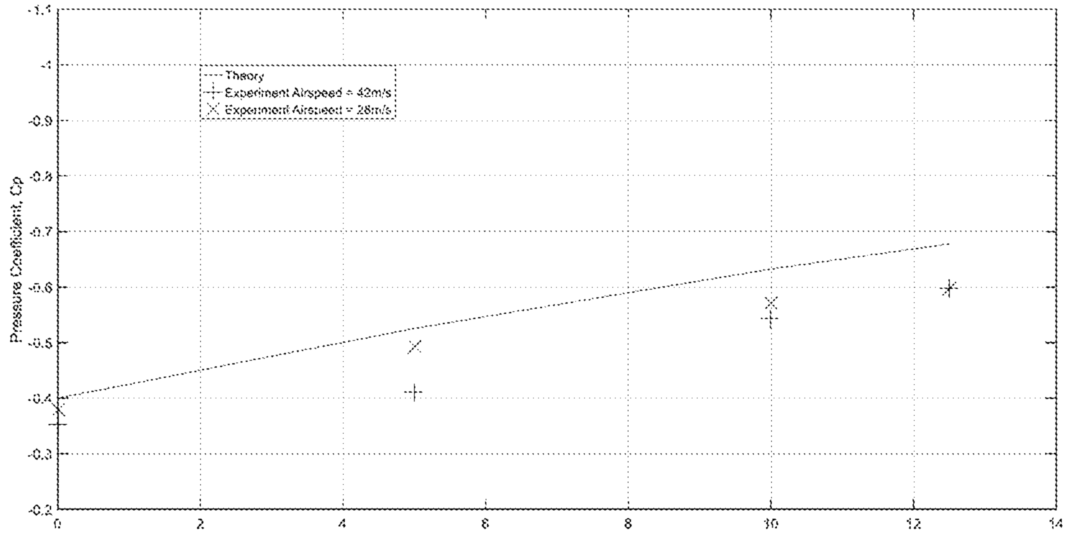


b) Chord Location, x/c = 0.10

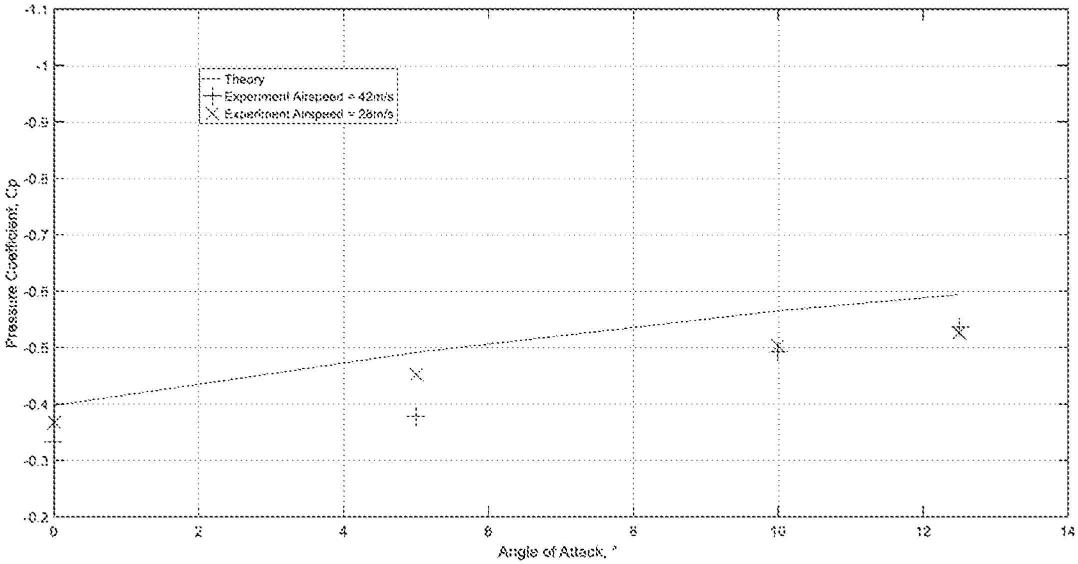


c) Chord Location, x/c = 0.15

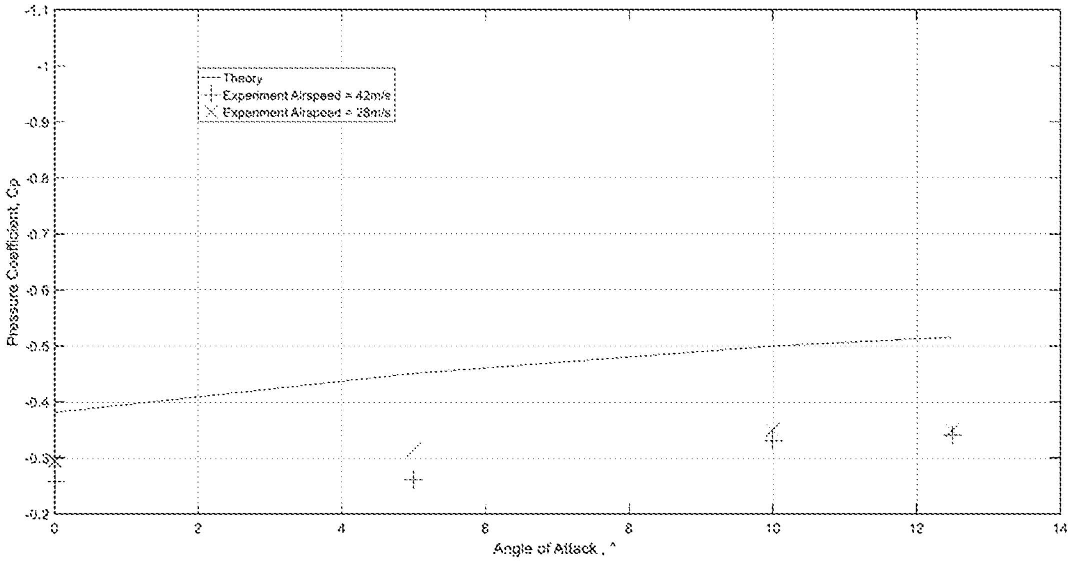
Figure 6



d) Chord Location, x/c = 0.20



e) Chord Location, x/c = 0.25



f) Chord Location, x/c = 0.30

Figure 6

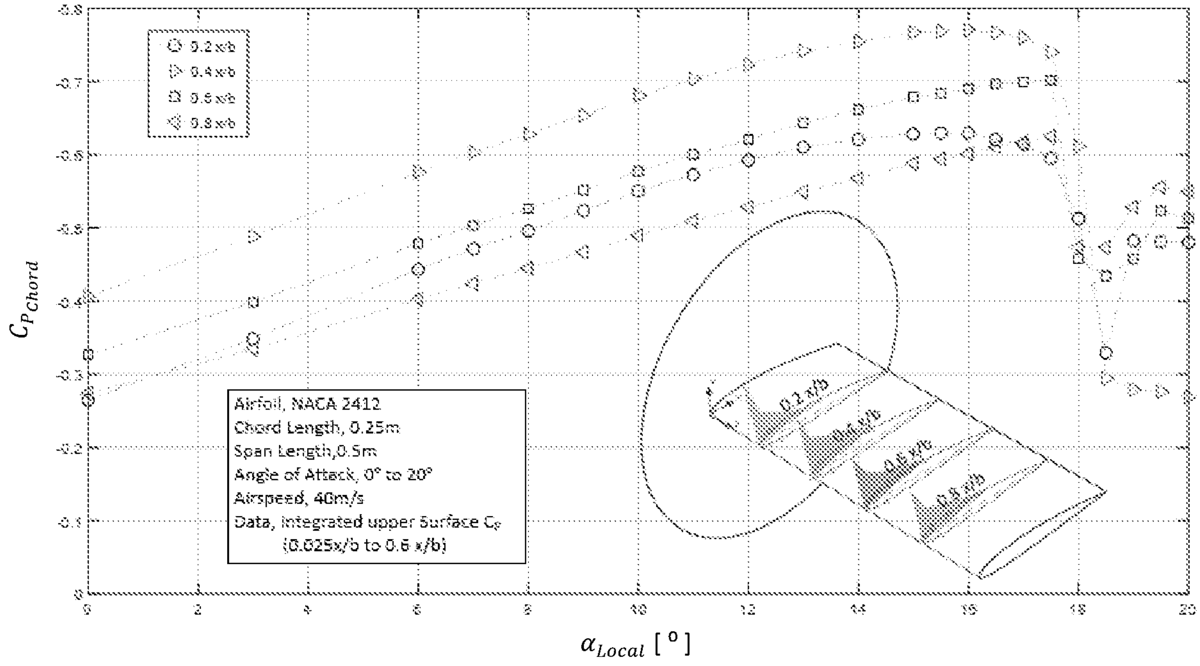


Figure 7

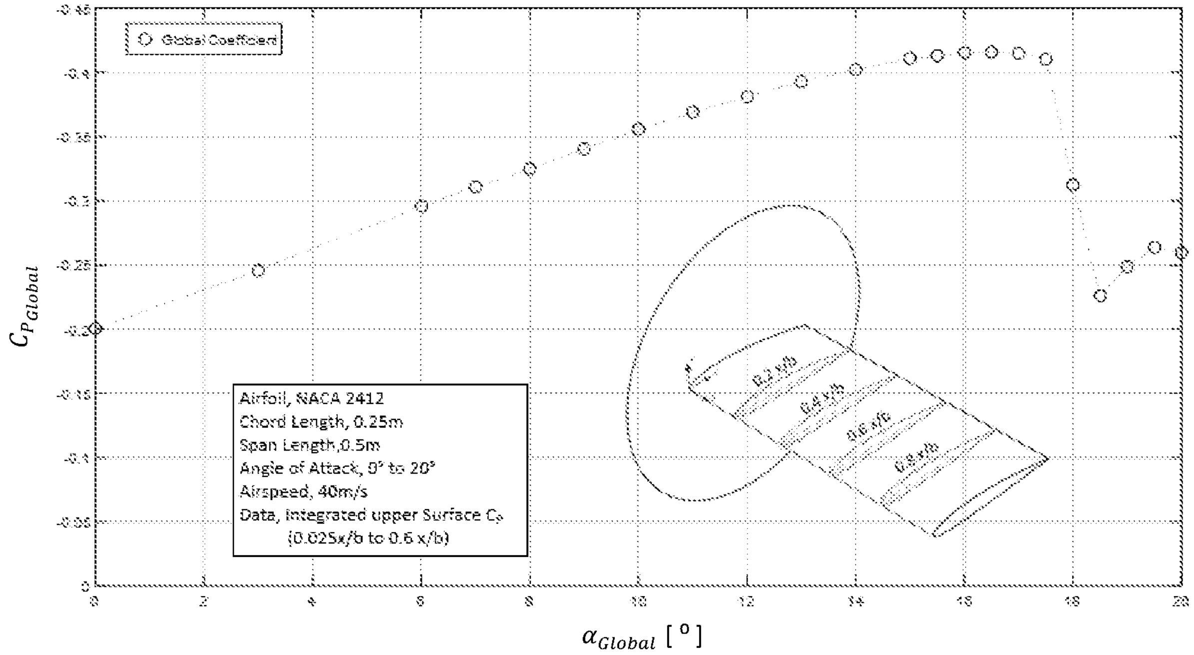


Figure 8

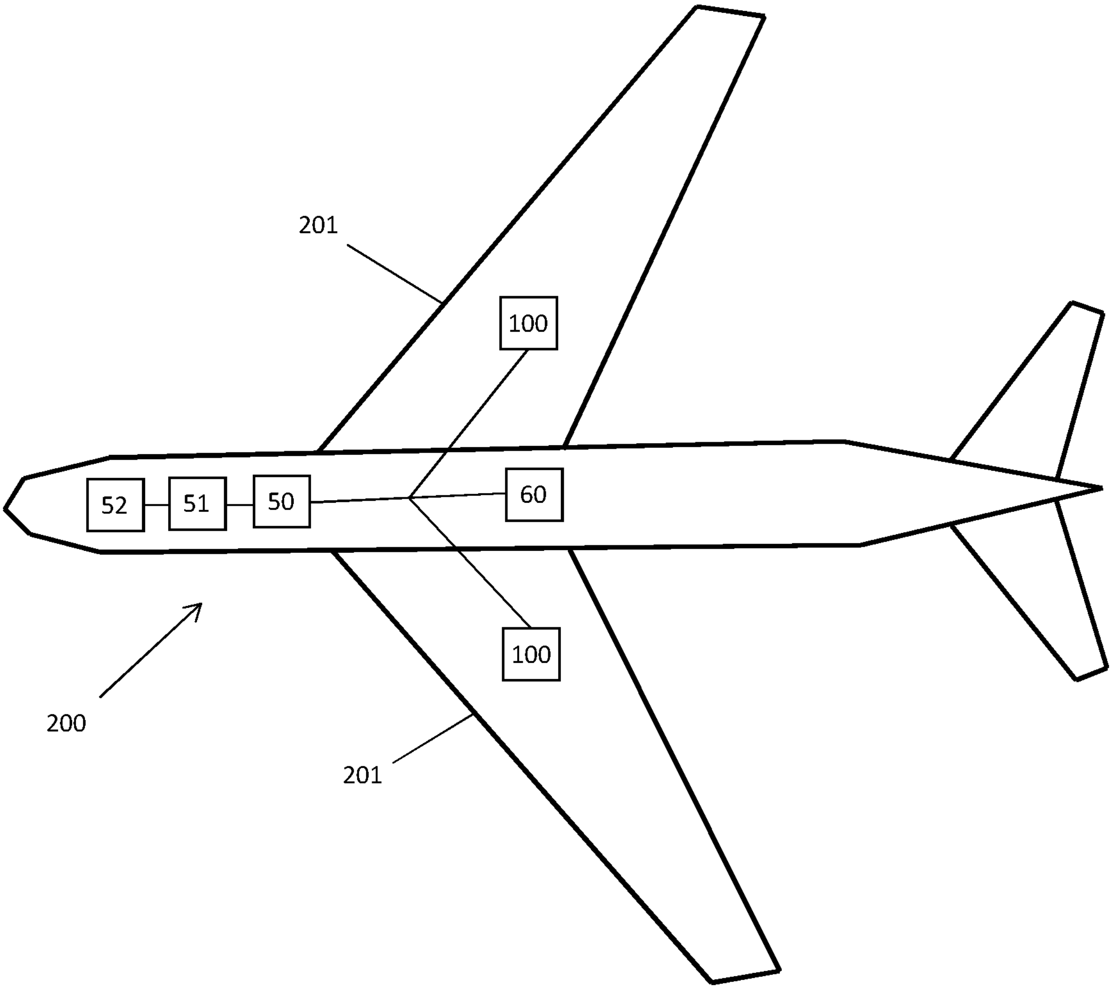


Figure 9

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2019/053662

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01M9/06

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/018703 A1 (MANGALAM ARUN S [US] ET AL) 15 January 2009 (2009-01-15) abstract paragraphs [0008], [0033] - [0035], [0040], [0045] figures 1-4 -----	1-26
X	CA 2 254 880 A1 (REDWOOD AIRCRAFT CORP [US]) 20 November 1997 (1997-11-20) abstract paragraphs [0026], [0033] -----	1-26
X	US 2010/274444 A1 (WILLIAMSON WALTON ROSS [US] ET AL) 28 October 2010 (2010-10-28) abstract paragraphs [0113] - [0116], [0119], [0123] figure 4 -----	1-26

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 20 April 2020	Date of mailing of the international search report 13/05/2020
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Daman, Marcel

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2019/053662

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2009018703 A1	15-01-2009	NONE	
CA 2254880 A1	20-11-1997	CA 2254880 A1	20-11-1997
		US 5769358 A	23-06-1998
		WO 9743176 A1	20-11-1997
US 2010274444 A1	28-10-2010	US 2010274444 A1	28-10-2010
		WO 2009091792 A2	23-07-2009