Sonic boom mitigation for hypersonic airliners engineering essay

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Abstract

Sonic boom overpressures propagated groundwards have resulted to the restriction of supersonic flight over land. It is therefore necessary to investigate mitigation methods to reduce the ground effects of sonic booms. An approach that has not been fully examined is the mitigation of sonic boom with the use of aircraft manoeuvres. In light of this, a computational method of graphically illustrating sonic boom overpressures on the ground has been developed in Microsoft Excel. This code can be used to set up a vast number of aerodynamic manoeuvres in the attempts of mitigation. As a result, it is possible to mitigate sonic boom overpressures into the air rather than groundwards by using an accelerated descent, followed by an ascent. It is essential that the turn is smooth and shallow in angle to minimise the caustic focusing effects. The ground pressure waves resulting in this manoeuvre are evenly distributed and less intense than that of a concentrated propagation. This research may therefore prove to be useful in the efforts to kick-start the use supersonic commercial transport overground

as the limitation of flight path is reduced if the manoeuvres are implemented.

List of Notations

a= speed of sound (m/s)c = Speed of Sound Relative to Aircraft Altitude (m/s)h = altitudeMa = Mach Numberr = radius of sphereR= Gas Constant (287m2/s2/K)Rp = Ground Propagation Radiuss = distanceT= Temperature (K)VAircraft = Velocity of the Aircraft with respect to the Mach Number (m/s)X = X-AxisY = Y-AxisZ = Z-AxisX0 = Centre of Sphere in X-PlaneY0 = Centre of Sphere in Y-PlaneZ0 = Centre of Sphere in Z-Plane= Mach Angle (degrees)= Degrees of a sphere (in steps of 10o)γ= Specific Ratio of Heats (1. 4 for Air)

Introduction

The supersonic flight era has produced much delight and controversy throughout its years. Here in 2013, we are left with zero supersonic commercial airliners due to the risk of human safety and the inability to maintain the aircrafts to the desired standards. The sonic booms produced by supersonic flight have led to the restrictions developed by the FAA to prohibit supersonic flight over-ground [11]. As an engineering challenge, there has never been a method developed to minimize or mitigate the sonic boom propagation to the ground fully. The aim of this project is therefore quite clear: understand and develop a sonic boom mitigation strategy. Minimization and mitigation strategies follow one of two paths; geometrically changing the shape, length and mass of the aircraft or, to alter the flight path by means of increased altitude, manoeuvres, acceleration and deceleration. Within this project, there is going to be an emphasis on the manoeuvres that aircraft can make to mitigate the sonic wave from ground propagation. In instances where the aircraft is manoeuvring, peak overpressures as high as 2. 5 times the maximum value of steady flight sonic booms can be produced [2]. This is the result of the U-wave overpressure or ‘ Superboom’. The focusing effects of the sonic waves that coalesce during a manoeuvre being performed develop a ‘ Superboom’. As an aircraft makes a turn, the waves will build up and merge at a focusing point. This point is related to the trajectory of the aircrafts turn but at a distance away from where the actual turn took place. Again, this can be accounted for due to wave propagation and diffusion. Manoeuvres such as steady flight acceleration, pushovers and 90-degree turns can focus the effects of sonic boom overpressure. These focusing effects will be fully scrutinized in the effort to mitigate the focused sonic boom away from the ground. If possible, these measures may be pivotal in the effort to successfully fly at supersonic speeds over-ground. This project has been undertaken in an attempt to fully investigate the consequences of putting an aircraft through a certain set of controlled manoeuvres, and therefore establish how they affect the sonic ground signature. This project is aimed to investigate if the controlled manoeuvres are a feasible mitigation strategy in the attempts of enabling aircraft to fly supersonic over-ground. In the attempt to complete and fully understand this project, the sonic waves will be modelled in excel for an airliner travelling at supersonic/hypersonic speeds. This will enable the ability to determine the effects of the controlled manoeuvres (turns, acceleration and deceleration) on the focusing aspect of the sonic boom footprint. It will therefore be possible to apply these results to define a set of guidelines that can be used to design flight-paths that mitigate the effects of sonic boom on the human population.

Assumptions and Limitations

Before hastily jumping into the coding aspect for graphically modelling the propagation of sonic waves, it is essential to take a step back and look at how the waves are to be modelled in Microsoft Excel. It is also critical, for the case of sonic boom propagation, to set atmospheric conditions due to the compressibility of air at supersonic speeds. For the ease of modelling sonic wave propagation, it is assumed that the atmospheric conditions are standard, isothermal, without winds, and constant for the duration of the analysis. These assumptions should not affect the general modelling of the waves for normal variations of the standard atmosphere (temperature profiles and winds). It is also sagacious to note that the air modelled in the flow is assumed to be isochoric (incompressible).[Eqn 2 – Mach Angle]Another simplification to this project is the assumption that the shape of the sonic boom wave, at altitude, is a perfect sphere with equation x2 + y2 + z2 = r2 [Eqn 1]. With a perfect sphere assumption, the Mach Cone angle is calculated by: Where = Mach Angle (degrees), c = Speed of Sound Relative to Aircraft Altitude (m/s) and VAircraft = Velocity of the Aircraft with respect to the Mach Number (m/s)As the atmosphere is standard without winds, this is a reasonable assumption to make and simplifies the analysis drastically.[Eqn 3 – Speed of Sound]The speed of sound for the propagation of the sonic boom sound waves has been calculated using data from [12] in respect to atmospheric temperatures at altitude. The speed of sound was therefore calculated using the following equation [13]: Where a= speed of sound (m/s), γ= Specific Ratio of Heats (1. 4 for Air), R= Gas Constant (287m2/s2/K) and T= Temperature (K). For the analysis of sonic boom mitigation using manoeuvres of the aircraft, the above, sonic wave propagation factor used [14], was an average value taken from the altitudes at which the centres of the sonic wave exits. This does not affect results for focusing of the sonic boom pressure waves due to the small difference in propagation speeds, and the limited effects they have during manoeuvres. For the purposes of this dissertation, looking into the effects of manoeuvres in supersonic flight, the aircraft will be simplified to a point source producing supersonic waves at time intervals of 1 second. This is a noteworthy simplification, as this project is not encompassing the effects of aerodynamic change to the aircraft on the ground signature it produces. It also reduces the complexity of modelling the sonic waves produced by the aircraft. Also for ease, the lift and drag factors have been neglected from the calculations are they should not alter the graphical representation of the supersonic ground signature. In terms of the graphical representation of the sonic wave propagation and ground signatures, the graphs will be limited to a quazi-three dimensional graph. These are essentially made up of a 2-dimension graph with a time element to make up the third. As far as the analysis of the mitigation strategy goes, this graphical illustration will be entirely acceptable.

Methodology

Graphical Implementation

[Eqn 4 – Sonic Wave Propagation]The first step of producing, graphically, a sonic wave footprint, is to model a stationary source emitting supersonic waves at set intervals. As mentioned in Section 4 – Assumptions, the sonic wave is to be modelled as a sphere. If this sphere is said to radiate at a rate proportional to the Mach Number and the change in time, we get the following from Eqn 1:[Eqn 5 – Time Dependent Sonic Wave Propagation]This can then be transformed into a time dependant equation as follows: From the above equation, it can be seen that the wave propagates radially at a rate dependent on the speed of sound, relative to the altitude, and the change in time (1 second for the purpose of this investigation). At each time step, the radius will enlarge in all x, y, z directions by a factor of the speed of sound as shown in figure 1 in red. This information however, does not fully depict the development of sonic waves from the source. The second aspect to incorporate is the movement of the sonic source (aeroplane), or in terms of the investigation, the lateral progression of the wave in the x-direction as shown in figure 1 in red: Z-AxisY-AxisX-Axis (Direction of Aircraft Motion)Figure 1 – Coordinate Axesr = a x ts = vaircraft x tThe lateral advancement of the first sonic wave is the result of the velocity of the aircraft multiplied by the time step. The velocity of the aircraft is predefined in Section 5 – Initial Conditions. The Mach cone can also be seen in blue in figure 1. The Mach angle, above and below the horizontal x-axis, can be calculated as shown in equation 2. Eqn 6 & 7 – Equation of MotionTo incorporate acceleration or deceleration of the aircraft, the following equation of motion was used: andThe above information permits critical information on each individual time-stepped sonic wave such as: the centre of the sonic wave (x-y coordinate) and the radial propagation. To fully understand and illustrate the effects of manoeuvres in supersonic flight, it was imperative that the sonic boom pressure waves intercepted the ground and left a signature. As this investigation focuses on the boom effects on the ground, altitudes must be set to replicate the condition of an aircraft approaching landing or taking off. With all of the previous considered, a code in excel was now be developed to begin the investigation of establishing the effects of implementing manoeuvres into supersonic flight.

Excel Implementation

In the aid of using Microsoft Excel to graphically represent the propagation of the sonic waves, an understanding in the method this programme plots data is required. Excel plots coordinates on x-y axes with data points from a series of coordinates. For each time step, a new data series is therefore required - yielding the 3rd time dimension along with the x-y axes. From Section 4. 1 – Graphical Implementation, the coordinates for the centre of each time-stepped sonic wave, along with the radial propagation could be calculated. For excel to plot each data series as a two dimensional sphere moving away from the aircraft according to equation 6, and radially dissipating with respect to equation 5, an array of x-y data coordinates are required. These points are formulated from the following equations:[Eqn 7 – X-Coordinate Points on Sphere][Eqn 8 – Y-Coordinate Points on Sphere]The theta value is the angle in degrees of the sphere in steps of 10o to 360o. The x-coordinates are calculated using equation 7, which calculates the x-coordinate using the angle of rotation and the cosine equivalent of that angle. The translates the angle in degrees to radians which allows excel to plot the values graphically. The y-coordinate calculation is identical to the x-coordinate with the one difference being the use of sine rather than cosine. Trigonometric relations can justify the use of sine and cosine to calculate the x and y coordinates. [Eqn 9 – Ground Propagation Radius]For the ground propagation graphs, a slightly modified version of equation 5 was used conducive to eliminating the sonic waves that do not produce a boom on the ground. The modified equation shown below incorporates the altitude and therefore only permits sonic waves with a ground footprint. In summary, with the use of equation 5, 6, 7 and 8, the sonic wave could now be modelled in Excel.

Initial Conditions

To accomplish the aims of this investigation, initial conditions must be set for the source (aircraft). These conditions will be kept constant which is critical to preserving the unbiased analysis. The analysis for the non-accelerated flights were carried out at M= 2. 5 for the average altitude of propagation during the flight. All ascending and descending trajectories were carried out at 420. 5m/s, which is equivalent to a 23o climb/ descent. Conditions for the accelerative flight were M= 2. 56 to M= 5. 45 at an average altitude of 3000m with a constant acceleration of 50m/s2. The decelerated flight conversely had an initial Mach number of 2. 5, which was decelerated, at 25m/s2, to M= 1. 1, also at an average altitude of 3000m. The outlandishly high altitudes were selected for illustrative purposes, as the effects of small accelerations were not quite so clear. Finally, the banked flight encompasses a planar movement, equivalent to the banking of an aircraft at 23o to show the effects of sonic boom focusing. This graph was only used to demonstrate the focusing effects of the sonic boom in air.

Results

The results for the sonic wave propagation for various flight paths can be seen to mitigate the sonic boom. The coloured spheres relate to the time element of the quazi-three-dimensional graph. The black arrows show the flight path the aircraft has taken whilst the black line represents the ground. Figure 2 is used to represent the results of a steady, non-accelerated flight at constant altitude and the resultant ground propagation. Figure 2. 1 – Linear Non Accelerated FlightFigure 2. 2 – Ground Signature for Figure 2. 1Figure 2. 2 represents the ground signature which the pressure waves in figure 2. 1 intercepted the ground. Figure 3. 1 – Focusing Flight Path 1Figure 3. 2 – Ground Signature for Figure 3. 1Figure 4. 1 – Focusing Flight Path 2Figure 4. 2 – Ground Signature for Figure 4. 1Figure 5. 1 – Accelerative Focus Flight PathFigure 5. 2 – Ground Signature for Figure 5. 1Figure 6. 1 – Decelerated Focus Flight PathFigure 6. 2 – Ground Signature for Figure 6. 1Figure 7 – Banked Flight 90 Turn

Analysis

As it can be seen in figure 2. 1, the effects of the sonic boom propagation are as previously stated in Section 4 – Methodology. The area encompassed by each sphere represents the distribution of the pressure wave. Inside those areas, a sonic boom will be detected. The most intense sonic boom overpressure is on the flight path, at the leading edge of the Mach cone. The intensity therefore reduces as the radial distance decreases towards the centre of the sphere. Moving to the ground signature shown in figure 2. 2, this is where greater attention is needed. At any particular instant, the pressure pulse is multiplied when a shock wave is intersected or touched by another. By and large, the greater the number of sphere that intersect a point, the greater the strength of the sonic boom pulse. This consequently demonstrates the prominence of looking for parts in an aircrafts flight, which spheres are concentrating. Figure 2. 2 illustrates this point nicely above and below the horizontal 11000m distance mark and again at 13000m. As explained previously, this would result in an enhanced ground overpressure resulting in much uproar if overground. It is of huge importance that these areas of intense sonic boom are mitigated from the ground signature. Figure 3. 1 shows the effects of low pass, initially descending and then ascending to the aircrafts final position. The pressure waves in this instance display an opposite effect as to what may is expected. This swoop mitigates the multiplied shockwaves and sends them into the air. The matter of the manoeuvre can explain this. If the manoeuvre can be thought of as an arc, with an inner radius (airward) and outer radius (groundward), the propagation of the shock waves are limited to the angles that are made by the turn. The inner arc displays an acute angle for the trajectory, where the outer arc produces an obtuse angle. For this case, the shock wave is more able to distribute evenly throughout an obtuse angle compared with the acute angle. This is displayed in figure 3. 1 with an even distribution of shock waves towards the ground and conversely a concentration of shock pulses in the air. The even distribution of shockwaves is also shown in the ground signature, figure 3. 2. It therefore can be said that manoeuvres in-flight can mitigate the effects of the pressure pulses on the ground. However, to understand the focusing effects of sonic boom, it is necessary to evaluate the cases where shock waves are focused on the ground. Figures 4-6 exemplify the affects of focusing the sonic boom pressure waves on the ground. The manoeuvres in these cases is a sharp ascent followed by a descent to level flight close to the ground. Figures 4. 1 and 4. 2 specifically, display the intensity of the sonic boom due to the manoeuvre. The boom is drastically concentrated around 10000m. Figures 5. 1 and 5. 2 represent the same flight path with acceleration. When accelerating, the shock waves are delayed which results in less concentrated pressure pulses on the ground as shown in figure 5. 2. This is a considerable reduction in the overall pressure wave concentration in figure 4. 2 and can be said to reduce the consequences of the manoeuvre. As the aircraft is accelerating, the pressure waves are regressing quicker than they are gaining on the accelerating aircraft. This results in a delayed effect with limited pressure wave concentration. Conversely, figures 6. 1 and 6. 2 have the opposite effect on sonic boom mitigation. As the aircraft is decelerating, the propagation speeds of the pressure waves are converging on the aircraft faster than the aircraft is advancing. This results in a build-up of pressure pulses, therefore focusing the sonic boom even greater. The 6000m-point would have to be avoided at all costs on the ground. Figure 7, finally shows a banked 90o right turn to illustrate the sonic wave concentration in the air. Again, this relates to the previous example in figure 3. 1. The inner arc displays the area of the greatest intensity, which should always be projected away from the ground.

Conclusion

With the above analysis, it is pertinent to avoid focused sonic overpressures propagating to the ground. The effects can therefore be minimised using manoeuvres in flight. This strategy proves to be theoretically effective in sonic boom mitigation.