MINIMIZING SONIC BOOM NOISE TO MEET POTENTIAL REGULATORY LIMITS

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1 Introduction

The boom produced by supersonic aircraft has prevented the introduction of new fast civilian air transports for the last 50 years. Proposed regulations would allow sonic booms of up to 75 dB of perceived noise level [1], which is very much less than the 110 dB sound signature of the Concorde, and which it is hoped will be acceptable to regulators and to the general public. Factors that affect the boom pressure and the sound levels perceived on the ground include aircraft weight and altitude, atmospheric conditions, and the aircraft shape and lift distribution. This study discusses the factors which can reduce the sound produced by a supersonic aircraft to an acceptable level.

2 Method

The code developed for this project predicts the sound pressure level which would be measured on the ground. The first step is to calculate the pressure signature in the vicinity of the aircraft, which is the near field sound level. Then, this signature is propagated through the atmosphere, taking into account the changes due to both the shaping of the shock wave and the attenuation of the atmosphere, to get the pressure on the ground. Finally, this pressure is converted to a perceived noise level (PLdB) to determine the effect on the observer. The maximum sound pressure is assumed to be directly underneath along the ground track, so this is what is calculated. The effect in the off track locations is assumed to be less.

2.1 Slender body in supersonic flight

A supersonic aircraft was first modelled as a slender cylinder in a uniform flow by Whitham,[2] which is a reasonable approximation to the long slender shapes actually used in high speed aircraft. The aeroacoustic pressure disturbance Δp at any position x and radius r from the aircraft is given by

$$\frac{\Delta p}{p_0} = \frac{\gamma M_0^2}{\sqrt{2\beta_0}} \frac{F(x)}{\sqrt{r}} \tag{1}$$

where M is the Mach number, $\beta = \sqrt{(M^2 - 1)}$, γ is the ratio of specific heats for air, and $F(x)$ is the Whitham "F Function

$$F(x) = \frac{1}{2\pi} \int_0^x \frac{S''(\xi) d\xi}{\sqrt{x - \xi}}, x > \xi \tag{2}$$

where S is the aircraft cross sectional area at station x, as determined by the aircraft geometry. Note that the F function depends only on variations of the body cross section area with length and represents the acoustic source signature. The pressure disturbance is a strong function of Mach number, but it decreases with distance only as $1/\sqrt{(r)}$, so it does not drop off very quickly.

The area function $S(x)$ represents the volume of air "pushed aside" and can be calculated for any reasonably slender shape. This produces a pressure function $P(x, r)$ at a distance r from the body, which propagates outward at the speed of sound. However, the local speed of sound will varies with pressure, so the x position of each point on the function will be changed to

$$x = \beta_0 r - kF(\xi)\sqrt{r} + \xi, k = \frac{(\gamma + 1)M_0^4}{\sqrt{2\beta_0^3}} \tag{3}$$

The modified function may be multivalued - that is, different pressures may be moved to the same position. This is the characteristic of a shock wave. The sound calculation code collects these different values and assigns a unique pressure to each point. This pressure becomes discontinuous, and forms the shock waves which are characteristic of the aircraft noise signature.

2.2 Aircraft Weight

Air is pushed out of the way by the aircraft's volume as it passes, and is also pushed downward to create lift. This produces an additional shock in the downward direction which adds to the sound underneath the aircraft. Harris [3] modifies the shape function $S(x, \theta)$ to be the sum of the cross sectional area $A(x)$ and a lift term $l(x, \theta)$ such that

$$S(x, \theta) = A(x) - \frac{\beta}{2q} \int_0^x l\,(x, \theta) dx \tag{4}$$

$$q = \frac{1}{2} \rho U^2 \tag{5}$$

where q is the dynamic pressure at aircraft speed U and atmospheric pressure ρ . The lift term reduces the area above the aircraft for positive θ and increases it beneath the aircraft. The lift distribution is a function of the aircraft geometry but the total lift in level flight must equal the weight. The lift term varies as $1/\rho$ and so increases with altitude. The volume term does not, so the lift effect becomes dominant at high altitudes. The lift term also varies as $1/U^2$, which counters the increase in sound due higher Mach numbers and makes the total sound almost insensitive to speed. The area function is also modified by the presence of engine inlets, since the amount of air pushed aside is reduced by what is taken in. This volume is added back at the exhaust. The theoretical maximum inlet area is in the Busemann biplane configuration, where all of the volume is taken in, and the shock effect is theoretically zero.

For a given aircraft shape and weight, the S function and the total sound intensity can be calculated at a given Mach number and altitude. Using the example of Airplane B in

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Maglieri [4] where the weight is 15,500 kg and the maximum area is $4\,m^2$ the S function is shown with separate weight and volume contributions in figure [1].

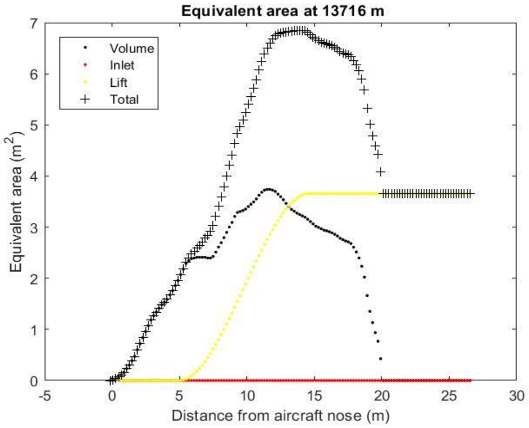

Figure 1: Contribution of volume and weight to total effective area for F-105 aircraft.

2.3 Sound Prediction

The above calculations give the sound signature in terms of a pressure profile, with sharp steps in pressure due to shock waves. The more useful result is the response of humans to these shocks, or the perceived sound volume, as determined by the frequency response of the human ear. The pressure was converted to a perceived sound level on the Stevens Mark VII scale, using the technique of Shepherd [5].

2.4 Aircraft Summaries

For conventional supersonic aircraft, the sound levels are calculated for a variety of weights and altitudes in figure 2 Weights over 100 tonnes are based on a Concorde shaped airframe, and lower weights are based on the F-105 shape as used in figure 2 Only the very lightest aircraft produce acceptable noise at 16 km altitude, and the heavier aircraft can only operate at 20 km, which is far above the maximum altitude normally used for civilian aircraft.

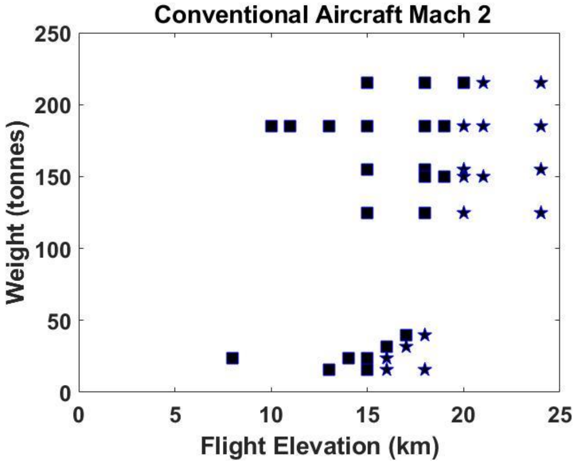

Figure 2: Conventional aircraft noise at Mach 2. Stars are values below the limit of 75 PLdB.

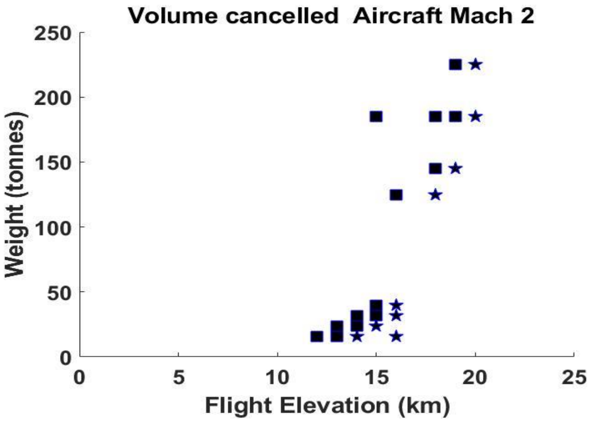

Figure 3: Theoretical volume cancelled aircraft noise at Mach 2.

To calculate the amount of sound reduction theoretically possible, the calculations were rerun without the aircraft volume term by using an engine inlet the size of the aircraft frontal area. The lift distribution has also been modified to be the entire length of the aircraft. Figure 3 shows that the acceptable weights and altitudes are slightly less restrictive, but are not dramatically better.

3 Conclusions

Using conventional technology, a supersonic aircraft flying at 2 at 16 km (50,000 feet) will have to weigh less than 40 tonnes, less than a small airliner like the A220 to meets the proposed noise standards, and one like the Concorde, with a maximum weight of 180 tonnes would have to climb to 20 km (66,000 feet) before going supersonic. A hypothetical aircraft with distributed lift and a volume-cancelling shape should be able to fly at Mach 2 at about 2 km lower.

References

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