Minimization of Sonic Boom on Supersonic Aircraft Using an Evolutionary Algorithm

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Abstract. The aerospace community has an increasing interest in developing super sonic transport class vehicles for civil aviation. One of the concerns in such a project is to minimize the sonic boom produced by the aircraft as demonstrated by its ground signature. One approach being considered is to attach a spike/keel on the front of the aircraft to attenuate the magnitude of an aircraft's ground signature. This paper describes an effort to develop an automatic method for designing the spike/keel area distribution that satisfies constraints on the ground signature of a specified aircraft. In this work a genetic algorithm is used to perform the design optimization. A modified version of Whitham's theory is used to generate the near field pressure signature. The ground signature is computed with the NFBOOM atmospheric propagation code. Results indicate that genetic algorithms are effective tools for solving the design problem presented.

1 Introduction

The minimum achievable sonic boom of any aircraft can be computed – it is proportional to the weight of the aircraft divided by its length raised to the 1.5 power [1,2]. Given that the minimum sonic boom can be computed, the natural extension is to attempt to design an aircraft so that its sonic boom is minimized. McLean [3] was the first to consider trying to achieve this objective by eliminating shocks in the ground signature of a supersonic aircraft.

The motivation for minimizing a sonic boom is many-fold, but the driving force behind the current effort is simply human comfort (from the perspective of an observer on the ground). The acceptability of a finite rise time overpressure as apposed to the N-wave shock structure was demonstrated in human subject tests [4,5]. This data indicated that a rise time of about 10 msec rendered realistic (0.6 psf) overpressures acceptable to all the subjects tested. Increasing rise time reduces the acoustic power in the frequency range to which the ear is most sensitive. Unfortunately, the aircraft length required to achieve a 10 msec rise

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time has consistently been proven to be impractical. McLean considered a Super Sonic Transport (SST) class vehicle (600K lb, flying at 60K ft and Mach 2.7) and concluded that a 570 ft long vehicle would be required (atmospheric effects resulting in midfield signature freezing were included).

Miller and Carlson [6,7] considered the projection of both heat and a force field upstream of a SST class vehicle. Their work focused on projecting a “phantom body” in front of the SST, with the goal of a finite (10 msec) ground rise time. Linear theory indicates that the optimum shape for a finite rise time is a 5/2-power area distribution (i.e., an isentropic spike). They concluded the power required to project the phantom body was the same as that needed to propel the vehicle. Marconi [8], using two-dimensional computational fluid dynamics, confirmed this power requirement. However, a significant wave drag reduction associated with replacing the vehicle nose shock with an isentropic pressure rise was also found.

There are a number of challenging problems associated with projecting anything far upstream of a supersonic vehicle. In particular, a significant reduction in efficiency is incurred when trying to project energy. These projection problems are avoided with the off-axis volume control introduced by Batdorf [9]. Figure 1 depicts his concept as implemented by Marconi et al [10]. Linear theory predicts that the asymptotic far field flow is independent of the details of the vehicle and is influenced only by the cross sectional area (and equivalent area due to lift) distribution of the configuration. In particular, in a supersonic flow the cross sectional area distribution in planes inclined at the Mach angle (μ in Fig.1) governs the far field flow downstream of those Mach planes. The theory predicts that whether the volume being cut is centered along the axis of the vehicle (i.e., a nose spike) or shifted off-axis (i.e., the keel of Fig.1) should not influence the resulting far field flow.

Batdorf’s concept was tested by Swigart [11] at Mach 2 and shown to be feasible. Swigart tested an equivalent body of revolution (typical of an SST) with an all-solid keel in addition to a keel with a portion of its volume replaced by a heated region. Swigart also tested a lifting wing body combination with an all-solid keel. The keels (both solid and thermal) were design to match the Mach plane area of a 5/2 power isentropic spike and achieved a nearly linear near-field pressure distribution as expected. The solid keel tested by Swigart was very large, extending the entire length of the configuration. Only the thermal keel that was tested seemed practical.

Marconi et al. [10] extended the Batdorf concept. In that study, the initial spike/keel sizing was accomplished using a modified version of the classical linear Whitham Theory [13], and detailed 3-D flowfields were analyzed using a nonlinear Euler solver. That study demonstrated that single keels produced significant 3-D mitigation over entire ground signature. In addition, they examined multiple approaches to minimizing the impact of the keel on the vehicle performance. Lastly, Marconi et al demonstrated that the spike/keel area distribution could be tailored to produce a desired ground signature.

The purpose of the present work is to develop an optimization procedure for the design of the spike/keel area distribution. A modified version of Whitham’s

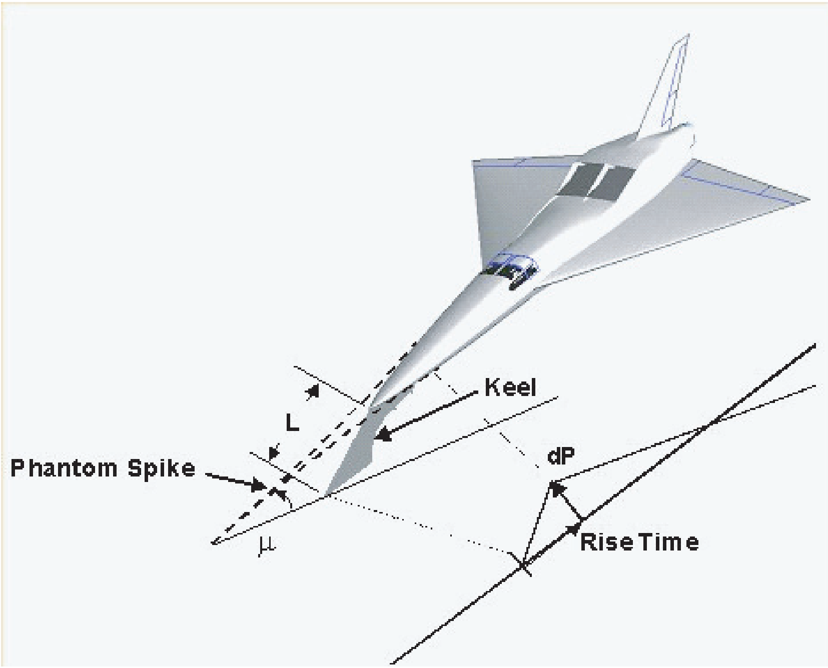

Fig. 1. Design Optimization - Genetic Algorithms (Forward Swept Keel → Length Amplification Factor = M_∞)

theory [12] is used to generate the near field pressure signature. The ground signature is computed with the NFBOOM [13] atmospheric propagation code. Genetic algorithms (GAs) are used for the optimization.

2 Flowfield Analysis – Genetic Algorithnm Fitness Function

Naturally, as in any GA application, determining a fitness function for the problem at hand is a central issue. In the current problem an attempt is being made to design a keel for a SST aircraft that will minimize the sonic boom felt on the ground. Thus, the fitness function must ultimately be able to take a keel design (the coding issue is addressed later) and provide a maximum decibel level in the associated ground signature.

Seebass [2] presents an algorithm for using linear theory to predict sonic boom ground signatures. In summary, the midfield pressure signature is computed from the aircraft equivalent body of revolution using the quasi-linear theory of Whitham [11] making far field approximations; i.e., computation of the "F-function". The midfield signature is then propagated to the ground using acoustic theory. A modified version of this theory (described next) was used for initial sizing of the phantom isentropic spike (dashed-lined-body extending the airplane nose in Fig.1).

In the present work, the far field approximations in the classical Whitham theory were relaxed; this was facilitated by the use of modern computational resources. Specifically, the small-disturbance perturbation velocity field solution, with the Whitham [12] modifications, to the linear form of the velocity potential equation,

$$\phi_{rr} + \phi_r/r - \beta^2\phi_{xx} = 0 \tag{1}$$

is given by

$$\begin{aligned} \frac{u}{U_\infty} &= -\int_0^y \frac{f'(\eta)d\eta}{\sqrt{(y-\eta)(y-\eta+2\beta r)}} \\ \frac{v}{U_\infty} &= \frac{1}{r}\int_0^y \frac{(y-\eta+\beta r)f'(\eta)d\eta}{\sqrt{(y-\eta)(y-\eta+2\beta r)}} \end{aligned} \tag{2}$$

In Eqn. (2), $y(x,r) = constant$ is the nonlinear characteristic curve along which $dx/dr = \cot(\mu+\theta) \approx \beta + (\gamma+1)M^4u/2\beta - M^2(v+\beta u) + o(u^2+v^2)$ [11]. Neglecting the second order terms, substituting for the velocity components [Eqn. (2)] and integrating $dx \approx [\beta + (\gamma+1)M^4u/2\beta - M^2(v+\beta u)]dr$ from the body surface results in

$$x - \beta r = \begin{cases} -\frac{(\gamma+1)M_\infty^4}{2\beta^2}\int_0^y \frac{\sqrt{(y-\eta)+2\beta r}-\sqrt{y-\eta+2\beta R_B}}{\sqrt{y-\eta}} f'(\eta)d\eta \\ -M_\infty^2\left\{\int_0^y \log\left[\frac{\sqrt{(y-\eta)+2\beta r}-\sqrt{y-\eta}}{\sqrt{(y-\eta)+2\beta r}+\sqrt{y-\eta}}\right] f'(\eta)d\eta \right. \\ \left. -\int_0^y \log\left[\frac{\sqrt{(y-\eta)+2\beta R_B}-\sqrt{y-\eta}}{\sqrt{(y-\eta)+2\beta R_B}+\sqrt{y-\eta}}\right] f'(\eta)d\eta \right\} + y \end{cases} \tag{3}$$

$y(x,r)$ is the value of $x - \beta r$ where the characteristic meets the body surface; $f(x)$ represents the source distribution, and when the tangency boundary condition is applied, $f(x) = A'(x)/2\pi$. Consistent with the small disturbance theory, the pressure field was computed from the linearized form of the compressible Bernoulli's equation ($p + \rho U^2 = constant$); i.e.,

$$\frac{p - p_\infty}{p_\infty} = -\gamma M_\infty^2 \frac{u}{U_\infty} \tag{4}$$

Using the above nonlinear characteristic theory improves the accuracy [12] over traditional linear theory, however multi-valued solutions due to wave crossing (break points) are possible. Physically, the overlap regions correspond to coalescence of the Mach waves into shock wave, followed by a discontinuous change in flow properties across the shock. Because near field solutions ($r/L \sim 0.2$) were computed here, break points were rare, and if they did occur, the spatial extent was very small. Hence, a simple shock-fitting algorithm, similar to that of Whitham was incorporated. The main simplification was that the shock was placed at the midpoint of the break region.

In summary, Equations (2-4), with 200 characteristics, were used to predict the velocity and pressure fields for a given airplane area distribution (with and without the isentropic spikes) including the additional equivalent area due to lift [2]. The integrals in Equation (2) were evaluated using a fourth order accurate numerical integration scheme; 5000 increments in η were used to ensure numerical convergence to within 0.1%. A computer program was written to perform this near field analysis. The program was validated with the 5/2-power frontal spike experiment given Swigart [11]; a comparison of the present algorithm to the experimental data is shown in Fig.2. The agreement was considered sufficient for the present sonic boom mitigation analysis.

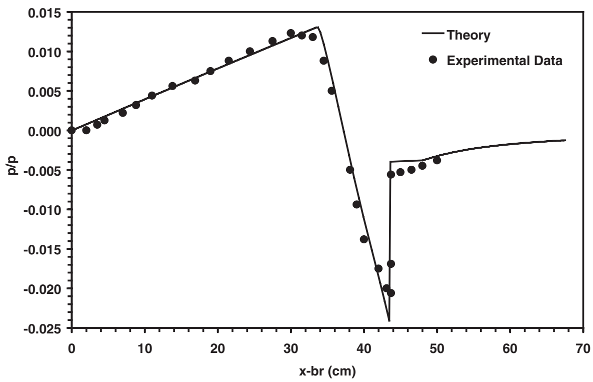

Fig. 2. Comparison of Quasi-Linear Theory with the Frontal Spike (r = 50.8 cm) Data of Swigart [11].

The near field solutions were extrapolated to the ground using the NASA Ames sonic boom FORTRAN routines in NFBOOM [13]. Specifically, the ANET subroutine, which extrapolates the signal through the non-uniform atmosphere, was incorporated into the Whitham theory program. A reflection factor of 1.9 was taken and no wind effects were assumed. In addition, the perceived ground pressure levels [4,5] were estimated with the PLdB subroutine also present in NFBOOM.

3 Design Optimization – Genetic Algorithm Coding Scheme

For sonic boom mitigation, the GA is given the task of minimizing the loudness of the sonic boom created by the body shape of the aircraft. This body shape is represented by graphing the effective area of the aircraft versus the position along the length of the aircraft. To optimize this body shape, an assumption is made that the body shape may be represented by continuous fourth-order polynomials.

The GA's task is then to modify the coefficients of this polynomial to minimize the loudness while also satisfying certain constraints that are placed on the body shape. One of the constraints placed on the GA is that the derivatives of the body shape must not fluctuate beyond a certain pre-set level. This is done to insure that the body shape will not be oscillatory in nature. Second, the GA must develop a body shape that visually lies between a "minimum" and "maximum" body shape. Thus, the plot of the polynomial generated by the GA must fit between two pre-defined curves. This focuses the scope of the GA's search and allows it to be more efficient.

In order to quantitatively evaluate the quality of each body shape that the GA proposes, each body shape is analyzed using Whitham theory. This results in a set of data that can then be read into NFBOOM program code to calculate the effective loudness of the sonic boom. This loudness serves as the driving factor of the GA's search. Those solutions with lower decibel levels are recombined with other quality solutions to form new solutions to test, while those solutions with higher decibel levels are discarded in favor of better solutions. This allows the GA to bias the population of potential solutions towards better solutions over time.

This approach of allowing a GA to propose coefficients of several fourth-order polynomials (constrained such that the first and second derivatives of the curve are continuous) allows for reasonable, if not effective, area distributions. Figure 3 shows a sample area distribution proposed by a GA.

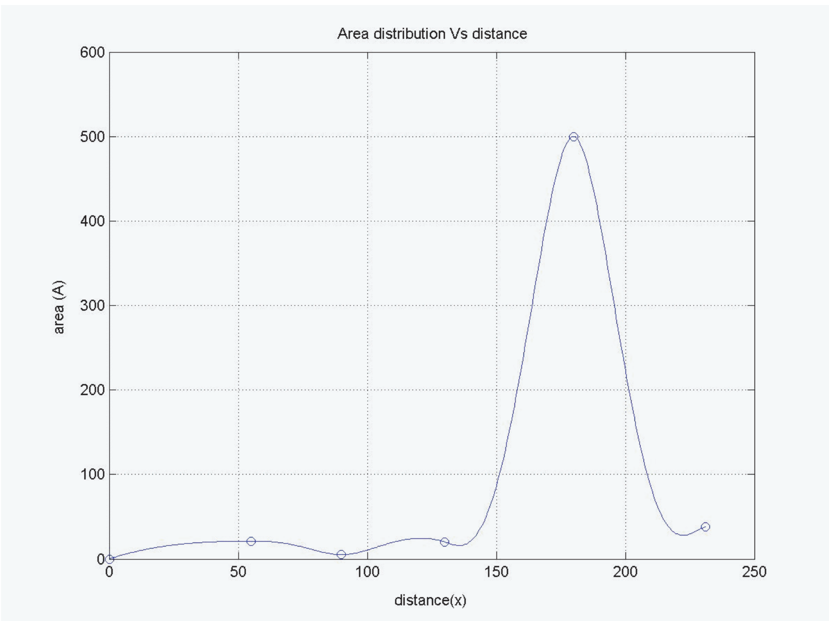

Fig. 3. Sample area distribution as proposed by a GA.

4 Results

With the definition of a fitness function and a coding scheme, a floating point GA can be used to effectively design keels that can be added to SST aircraft that minimize the sonic boom for given flight conditions. For this study, the following GA parameters are used:

- *population size* = 50
- *maximum generations* = 250
- *mutation probability* = 0.3
- *mutation operator* = Gaussian mutation
- *crossover operator* = standard two-point crossover

The remainder of this section describes the effectiveness of the GA in determining keel designs.

4.1 Initial Isentropic Spike Design

Phantom isentropic spikes (extending the nose of the airplane as shown in Fig.1 and 2) were designed to lower the initial shock pressure rise to 0.3 psf (Marconi et al [10] goal). The length and strength (K) of the 5/2-spike ($A = Kx^{5/2}$) were the design parameters. The spike was blended to the body, and the body geometry was fit with five fourth-order polynomial curves. The coefficients were selected to ensure that the body fit was continuous through the third derivative. Figure 4 shows an example aircraft area distribution (including the equivalent area due to lift) with the isentropic (forward) spike and the body fits. This parameterization proved sufficient for all configurations tested. Because the 5/2-spike removes the shock wave altogether, the perceived sound level (PLdB) [4] was used to convert the linear ground-signature waveform sound level into an equivalent-shock-wave signature, where the perceived sound levels were matched. Figure 5 shows an example result, where a spike was designed to reduce the initial shock pressure rise from just over 0.6 psf for the baseline aircraft down to 0.3 psf (the design goal). The length of the corresponding swept forward keel [10] would be 8.1% of the baseline aircraft length.

4.2 Initial Genetic Algorithm Designs – Feasibility Study

The first step in determining the effectiveness of using a GA to perform keel design for sonic boom mitigation is to match published data. As described in Marconi et al. [10], the upstream spike area distribution can be used as a design variable to produce a desired ground signature. Hence, it the present work, the 5/2-spike requirement was relaxed, and genetic algorithms were used to produce an "optimum" design. In the present work, the optimum was determined to be the shortest spike/keel that produced a ground signature shock overpressures < 0.3 psf; signatures with multiple shocks that met this requirement were acceptable.

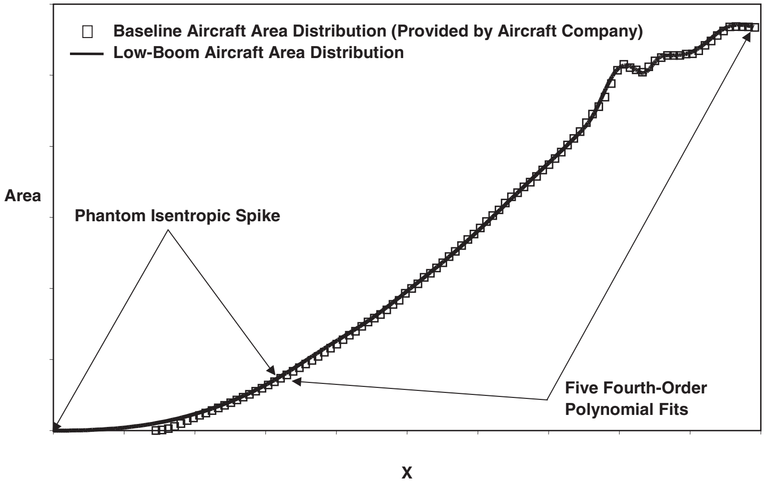

Fig. 4. Example Equivalent Mach Plane Area Distribution (Scales intentionally left blank).

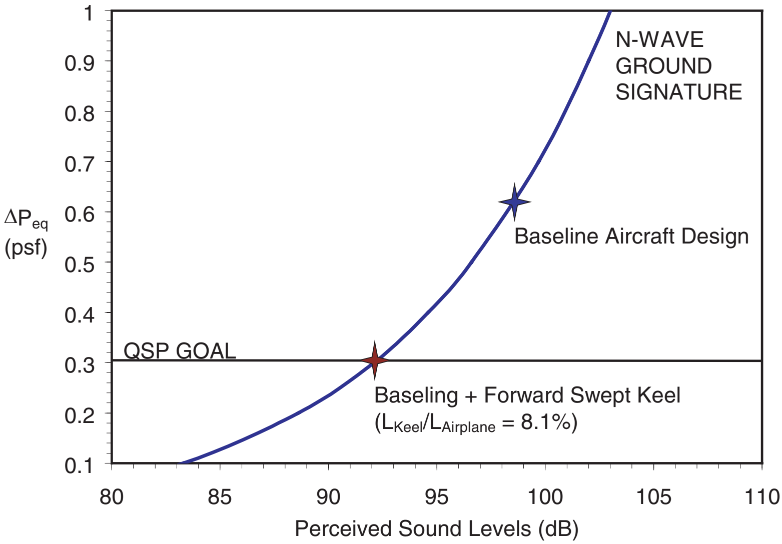

Fig. 5. Example Boom Reduction Results.

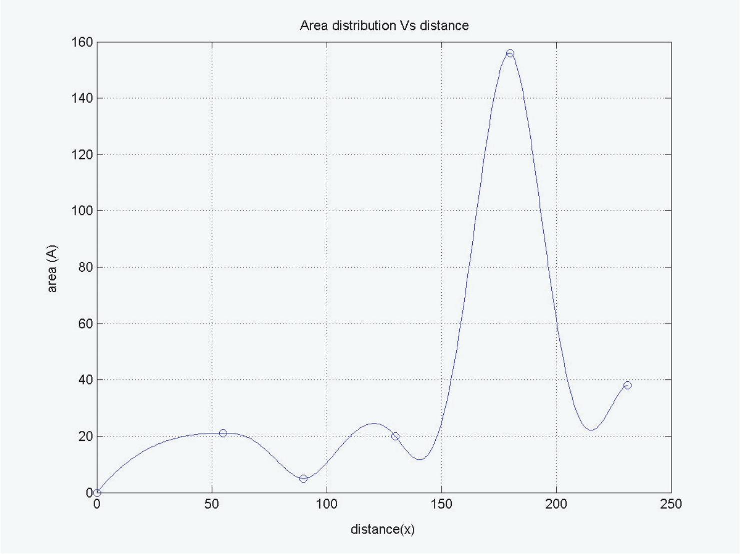

Fig. 6. The area distribution above represents the best solution determined using a GA.

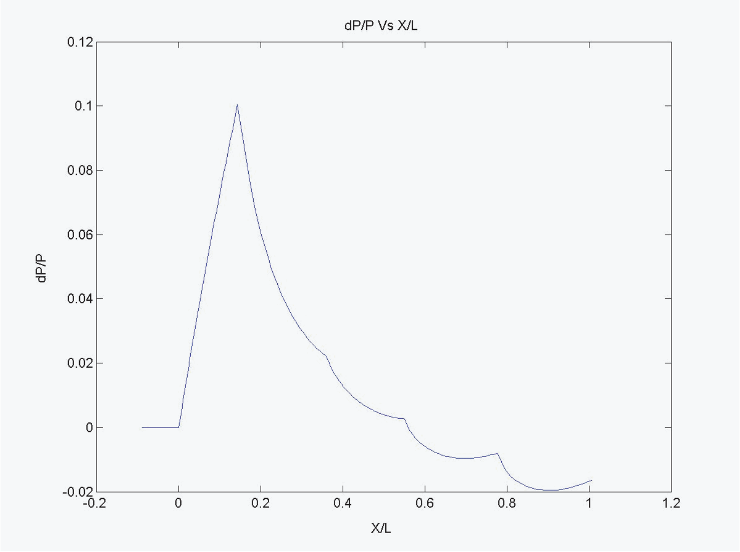

Fig. 7. The ground signature above results in a sonic boom of magnitude 104.0 dB.

Given the GA's ability to solve this simple design problem, the more complex problem of determining a keel shape that minimizes the decibel level in a ground signature was undertaken.

4.3 Initial Genetic Algorithm Designs – Feasibility Study

Based on the results presented in Fig.4 and 5, the GA was considered to be an appropriate tool for determining the keel shape (as depicted in an area distribution) that minimizes the sonic boom of a SST aircraft. Figures 6 and 7 show the optimal design and associated ground signature determined in this manner. It is important to note that the GA found a design that had a sonic boom of magnitude 104.0 dB; the best solution to date determined by a human designer had a sonic boom of magnitude 106.3 dB.

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Nomenclature

A Airplane Area Distribution
K 5/2-Area Distribution Strength (i.e., $A = Kx^{5/2}$)
L Length
M Mach Number
p Pressure
R_b Body Radius
r Radial Coordinate
u Axial velocity perturbation
U Axial Velocity
v Radial velocity perturbation
x Axial coordinate
y Curved Characteristic Line
β $\sqrt{M^2 - 1}$
γ Ratio of Specific Heats
μ Mach Wave Angle
ρ Density

Subscripts

∞ Flight Condition at Altitude