Optimization of Nose Shape for Reduction of Sonic Boom

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Abstract

Sonic boom is one of the environmental problems produced by aircraft, and reduction in its peak pressure is a significant subject assosiated with the development of supersonic transport (SST). Recently various low boom configurations are being suggested. In the present study, a Genetic Algorithm (GA) has been applied to aerodynamic shape optimization of an axisymmetric nose (forebody) geometry. The peak overpressure of sonic boom is obtained from an extrapolation of the near-field pressure signatures with the waveform parameter method. The drag of designed object is calculated based on the pressure ditribution along the body surface, which is obtained by solving the Euler equations. In order to reduce the number of function evaluations by CFD up to the global optimal solution, a method by the use of approximated functions is proposed.

1. Introduction

In recent years supersonic transport is expected to be developed in order to satisfy the demand of increasing passengers worldwide, especially in Pacific route. However, supersonic transport cannot be realized without solving environmental problems, such as ozone depletion by aircraft exhaust, engine noise at take-off and landing, and sonic boom generation by supersonic flight. In this study, we focus on the sonic boom problem.

When aircraft cruises at supersonic speeds, shock waves are generated and accumulated during their propagation, leading to an N-shaped wave in the far-field.[1,2] This is called sonic boom, which can be heard as two booms in rapid succession and gives an unpleasant noise to us and animals on the ground. The intensity of sonic boom is related with the peak overpressure of the N-shaped wave.

One of remedies for reducing sonic boom is to produce a strong bow shock by employing a blunt nose and to delay the accumulation of shock waves in the far-field. However, this method has a paradox that the blunt nose makes the drag increase. Therefore a trade-off between low boom / high drag and high boom / low drag should be taken into consideration (Fig. 1).[3-6]

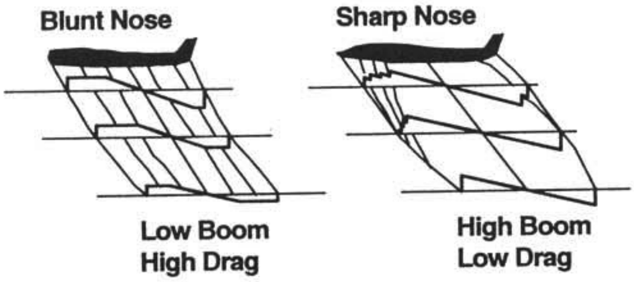


Fig. 1 The low-boom high-drag paradox.

From this point of view, aerodynamic shape optimization is needed in order to find a low boom / low drag configuration. Previously we optimized the configuration of supersonic transport with a Genetic Algorithm (GA), by using the modified linear theory and the slender body theory. As a result, the peak overpressure was greatly reduced without increasing drag. On the other hand we also calculated the near-field pressure signatures around an axisymmetric body by CFD and could adequately capture change of pressure signatures in accumulation process.

In this study an aerodynamic shape of supersonic transport is optimised with a combined method between CFD and optimization.[7-8] However, since GA requires a large number of evaluations, it is not efficient, compared with the conventional optimization methods. Therefore we propose an optimization method, which can lead to an optimal solution using a small number of calculations by CFD. A nose shape is selected as an object to be optimized because the characteristics of front-shock greatly affect reduction in sonic boom. The design variables are the radii of several cross sections of an axisymmetric nose shape. The near-field pressure signatures obtained from the results of CFD are extrapolated to obtain the pressure signatures on the ground,[9-11] the characteristic features of which are evaluated with a designer's evaluation function.

2. Method of Optimization

2.1 Genetic Algorithm

Genetic Algorithm (GA) is a computational model that emulates biological evolutionary theories to solve optimization problems. GA comprises a set of individual elements referred to as a population and a set of biologically inspired operators defined over its population. According to evolutionary theories, only the most suited elements in a population are likely to survive and generate offspring, thus transmitting their biological heredity to new generations.[12,13]

A whole new population of possible solutions is thus produced by selecting the best individuals from the current generation, and mating them to produce a new set of individuals. This new generation contains a higher proportion of the characteristics possessed by good members of the previous generation. In this way, over many generations, the good characteristics are spread throughout the population, being mixed and exchanged with other good characteristics. By favoring the mating of the fittest individuals, the most promising areas of the search space are explored. If a GA has been designed well, the population will converge to an optimal solution to the problem.

The power of GA comes from the fact that the technique is robust, and can successfully deal with a wide range of problem areas, including those which are difficult for other methods to solve. Though GA is not guaranteed to find the global optimum solution to a problem, it is generally good at finding allowable good solutions to problems with an acceptable speed.

In general, GA is composed of four major steps: evaluation, selection, crossover, and mutation. In this study, the population has a micro size in order to reduce the number of function evaluations to find a global optimal solution. Regarding operators, tournament selection and uniform crossover are used, and the micro-GA is employed as an operator, which introduces new genetic structures in the population at random, and plays a role similar to the mutation (Fig. 2). The micro-GA checks the convergence of micro population. If the population is converged, it restarts a new generation with a best individual and others chosen at random.

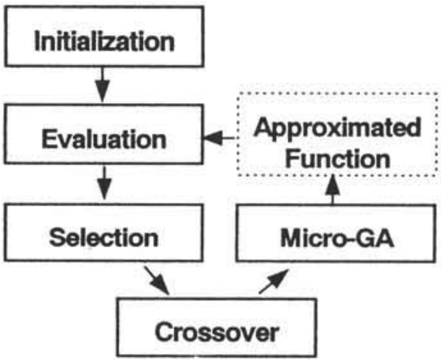


Fig. 2 Procedure of Genetic Algorithm.

2.2 Function Approximation

Generally, it is only once in the process of selection that the values of a fitness function evaluated by CFD are used. For that reason, most of the evaluated values are in vain. However, the values calculated by CFD compose a part of a design space, so that it is more advantageous to use them in order to accelerate convergence in the GA. Therefore, in this study, approximation functions are constructed using several values calculated previously in the process of evaluation.

The function F has been formulated using a polynomial in the following formulation:[14]

$$F = A_0 + \sum_{i=1}^{n} \sum_{j=1}^{2} A_{ij} x_i^j$$

where n is the number of dimensions, i.e., design variables, A_{ij} are the coefficients to be calculated, and x_i are the terms of a polynomial for each dimension. Using the data supplied by CFD, the coefficients A_{ij} are obtained by solving the simultaneous equation.

In this study, approximated functions are constructed for every generation, and approximated optimal solutions are found based on these approximated funtions. They are added as an individual to the next generation after the operation of the micro-GA.

3. Formulation of Optimization Problem

The design goal of the present study is to determine the geometry of an axisymmetric nose (forebody) that minimizes the intensity of sonic boom on the ground. In this investigation, since the body shape is not defined by a linear combination of a relatively small number of base analytical functions, a more general body shape definition has to be used. As shown in Fig. 3, three cross sections are defined between the tip and the end of the nose part. At each of these cross sections the radius r_i is specified. By fitting cubic splines between the radii and enforcing an equal slope constraint between successive splines, the profile of the nose part is defined. A full rotation of this profile creates the three-dimensional shape. Each radius can take any value within its upper and lower bounds, providing an infinite number of possible solutions.

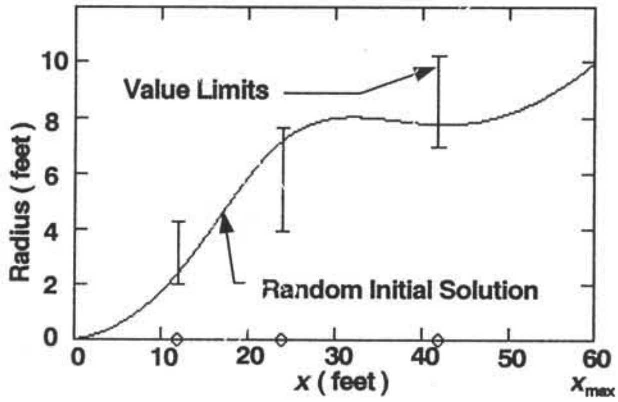


Fig. 3 Geometric definition of nose profile with radii defined at 3 cross sections.

The design optimization problem can be formulated as follows:

min Δp (the peak overpressure level on the ground)

under the following conditions:

$$0.033\, x_{max} \leqq r_1(x_1) \leqq 0.071\, x_{max}$$
$$0.066\, x_{max} \leqq r_2(x_2) \leqq 0.128\, x_{max}$$
$$0.117\, x_{max} \leqq r_3(x_3) \leqq 0.171\, x_{max}$$
$$(x_1 = 0.2\, x_{max},\ x_2 = 0.4\, x_{max},\ x_3 = 0.7\, x_{max})$$

The flight conditions are supersonic (Mach 2.0) with zero angle of attack and zero lift. x_{max} is the length of a nose part, which is equal to 60 ft, where x is the axis of body. The cross-sectional radius at the end is fixed at 1/6 x_{max}, which is equal to 10 ft. The body flies at an altitude of 50,000 ft and the peak overpressure level of sonic boom is evaluated on the basis of the pressure signatures on the ground, which is obtained from an extrapolation of the near-field pressure signatures with the waveform parameter method.

First, we consider a problem to minimize the aerodynamic drag for an axisymmetric nose in order to examine whether or not this GA works well.

This problem can be formulated as

$$\min\ C_d = \int_{tip}^{end} p(x) \cdot dS_y(x) \Big/ q_\infty \cdot S_y^{end}$$

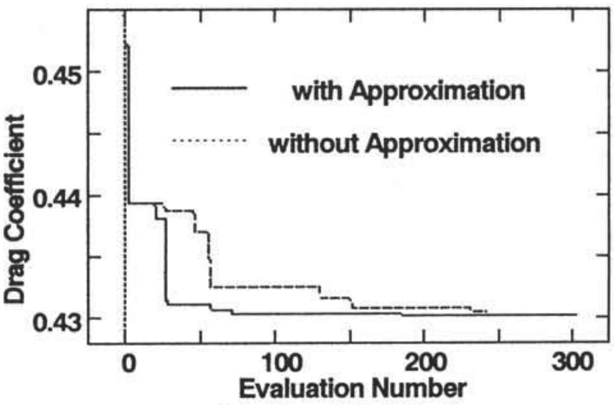
under the same conditions as the above-mentioned, where $p(x)$ is the pressure at a position of x. q_∞ is the dynamic pressure of uniform flow. $dS_y(x)$ is the projection of an increment of the body surface area to the plane vertical to the x axis, which is equal to $d(\pi(y(x))^2)$. S_y^{end} is the cross-sectional area at the end ($x = x_{max}$).

4. Results

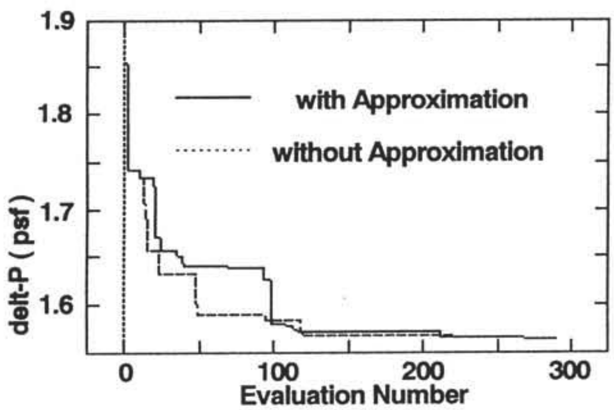
In the present study, the number of individuals per generation is seven and optimization is carried out up to the hundredth generation with GA.

First, in order to verify the performance of GA, aerodynamic drag was minimized using two methods. Case 1-a is GA without approximated functions, while case 1-b is GA with approximated functions. The actually required time for optimization is determined by not the number of generations, but the number of fitness function evaluations with CFD. Figure 4 shows the number of evaluations by CFD it takes for GA to obtain the optimal solution. These results show that the best individual for case 1-b performs better than for case 1-a in any evaluation number, and that the use of approximated functions accelerates the optimization process. Only the optimal nose geomtry for case 1-b is presented here, because both cases show almost the same results. The obtained minimum drag shape (Fig. 5) agrees remarkably well with the theoretical one derived by Parker using the linearized supersonic theory.[15] This proves that GA works well in the present problem.

Then, the peak pressure level of sonic boom was minimized using the two methods mentioned above. That is, case 2-a is GA without approximation, while case 2-b is GA with approximation. Contrary to the aerodynamic drag minimization problem, case 2-b shows slower progress of optimization than case 2-a (Fig. 4). In the case of aerodynamic drag minimization, approximated functions can well fit the distribution of the fitness function. However, in the case of sonic boom minimization problem they fail to do so, because the function takes a more complicated form. Nevertheless, after a hundred of evaluations by CFD, when the value of the fitness function almost reaches the minimum, the value of the best individual for case 2-b is almost equal to that for case 2-a. Therefore, it does not seem that the use of approximated functions exerts a bad influence on optimization.



(a) Drag Minimization



(b) Sonic Boom Minimization

Fig. 4 Convergence histories for two methods with and without approximated functions.

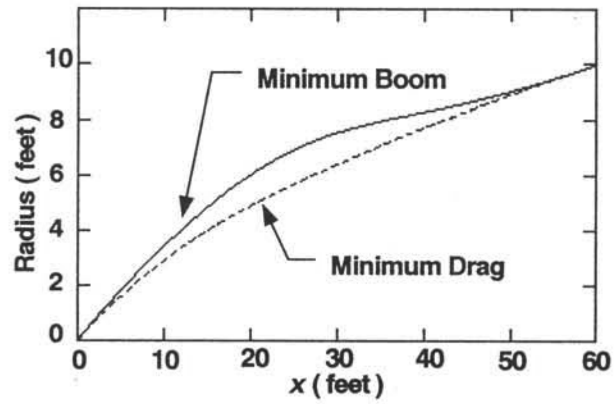


Fig. 5 Optimized geometries with regard to sonic boom and drag.

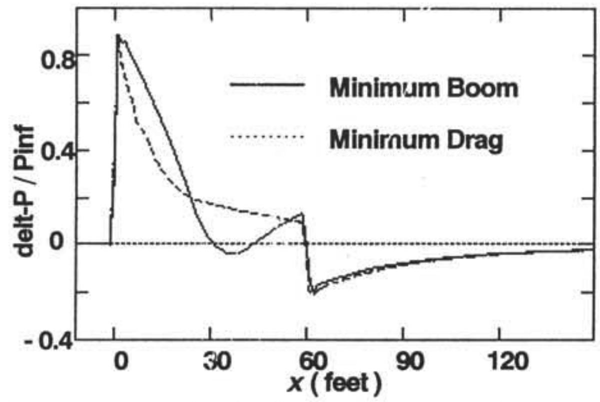


Fig. 6 Pressure distributions for optimal solutions along the body surface.

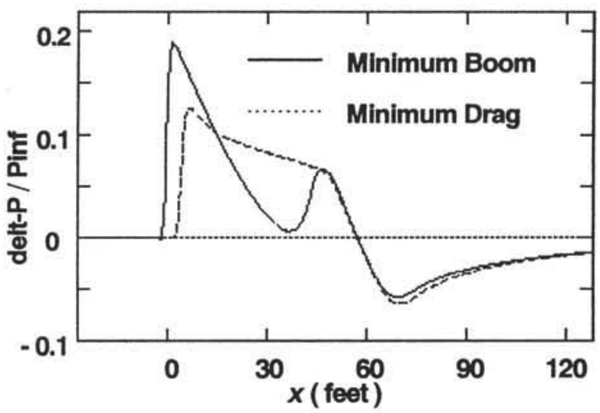


Fig. 7 Pressure distributions at $r = x_{max}$.

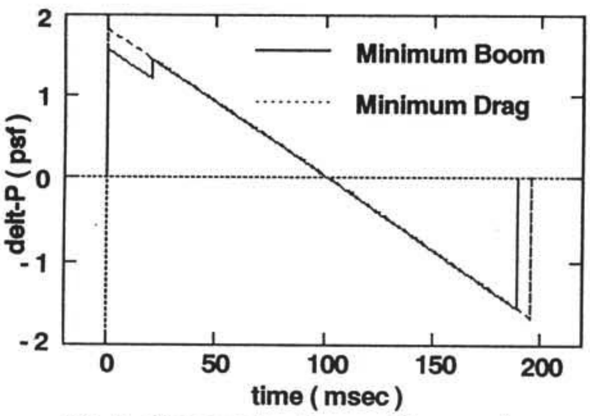


Fig. 8 Pressure signatures on the ground.

The characteristics of the optimal solution to minimize sonic boom is compared with that for aerodynamic drag. The shape of the best individual for case 2-b projects outward than that for case 1-b, but the slopes of both geometries near the end become almost the same (Fig. 5). In the pressure distributions (Fig. 6), the pressure increases at the nose tip by the shock show the same level. In case 1-b, the pressure drops suddenly downstream of the shock and then decreases gently. On the other hand, the optimal solution for case 2-b has the characteristics that the second pressure rise occurs after the pressure decreases at a constant rate toward the downstream from the shock. These results suggest that the aerodynamic drag increase for case 2-b is caused by the smaller pressure decrease rate near the nose tip and the larger projection to the plane vertical to the x-axis.

Regarding sonic boom, in case 2-b the near-field pressure at $r = x_{max}$ decreases up to 30 ft from the shock wave toward the downstream, where the amplitude of pressure is reduced with the same distribution profile as that along the body surface. However, in case 1-b the near-field pressure is greatly attenuated only at x = 0-12 ft, where the pressure on the body surface greatly decreases in the downstream direction, and is not at x = 12-48 ft, where the surface pressure gently decreases (see Figs. 6 and 7).

Pressure signatures on the ground are shown in Fig. 8. While the pressure signatures of the optimal solution for case 1-b form a perfect N-shaped wave and its peak overpressure level is 1.81 psf (86.7 Pa), the overpressure level for case 2-b is 1.56 psf (74.7 Pa). It is concluded that large attenuation of the first shock and small increase by the secondary shock prevent an increase in the overpressure level due to the rear shock (see Fig. 8).

5. Concluding Remarks

The use of approximated functions cannot always accelerate the convergence in any optimization problem. However, it is effective to make use of the information obtained from CFD in the evaluation process in some fashion. Hence, to minimize the intensity of sonic boom, more appropriate approximated functions are needed to be devised, which makes the convergence of optimization accelerate, leading to the shorter calculation time.

Though in the present study the number of geometry parameters is as few as three, which is a possible minimum, the peak overpressure level was surely reduced and a low-boom geometry was obtained. It is expected that more suitable geometries will be available by increasing the number of parameters.

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