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Research of low boom and low drag supersonic aircraft design

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Abstract Sonic boom reduction will be an issue of utmost importance in future supersonic transport, due to strong regulations on acoustic nuisance. The paper describes a new multi-objective optimization method for supersonic aircraft design. The method is developed by coupling Seebass–George–Darden (SGD) inverse design method and multi-objective genetic algorithm. Based on the method, different codes are developed. Using a computational architecture, a conceptual supersonic aircraft design environment (CSADE) is constructed. The architecture of CSADE includes inner optimization level and out optimization level. The low boom configuration is generated in inner optimization level by matching the target equivalent area distribution and actual equivalent area distribution. And low boom/low drag configuration is generated in outer optimization level by using NSGA-II multi-objective genetic algorithm to optimize the control parameters of SGD method and aircraft shape. Two objective functions, low sonic boom and low wave drag, are considered in CSADE. Physically reasonable Pareto solutions are obtained from the present optimization. Some supersonic aircraft configurations are selected from Pareto front and the optimization results indicate that the swept forward wing configuration has benefits in both sonic boom reduction and wave drag reduction. The results are validated by using computational fluid dynamics (CFD) analysis.

1. Introduction

Over the past several years, there has been a renewed interest in supersonic aircraft for civil applications. This resurgence has been partly motivated by significant developments in modeling and simulation, including improved shape optimization capability, novel concepts for supersonic drag reduction; shape-based boom tailoring techniques, and their validation using a flight demonstrator. Low boom supersonic aircraft design remains one of the most challenging aircraft design problems, which is a truly multidisciplinary design problem that frustrates many talented aircraft designers. A number of scientists believe that a key requirement for the economic viability of the supersonic transport is its ability to operate at supersonic speeds without restriction over land.[1]

Choi et al. researched the multi-fidelity design optimization of low boom supersonic jets based on response surface

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method,[2] and they constructed a two-level multi-fidelity optimization frame for supersonic jets design.[3] Laban and Herrmann constructed a frame for multidisciplinary analysis and optimization of supersonic aircraft, and optimized the aerodynamic and structure.[4] Takeshi and Yoshikazu optimized the supersonic aircraft for low boom and low drag in traditional method.[5] Wu et al. researched the mixed fidelity approach for design of low boom supersonic aircraft by using computational fluids dynamics (CFD) and Seebass–George–Darden (SGD) inverse design method.[6] Chung and Alonso researched the multi-objective optimization using approximation model-based genetic algorithms.[7] Sasaki and Obayashi researched the low boom optimization method based on CFD and genetic algorithms.[8] Tejtel et al. constructed a conceptual aircraft design environment.[9] Haas and Kroo developed a multi-shock inverse design method for low boom supersonic aircraft.[10] Kusunose et al. used a new biplane concept to reduce the sonic boom.[11] Wintzer et al. developed a new multi-shock inverse design method for low boom supersonic aircraft design and the optimization is based on response surface model.[12]

Traditional optimization method has some difficulty in suppressing the sonic boom. But on the other hand, inverse design method such as SGD method has a significant increase of drag. So we combine the low boom inverse design method and traditional genetic algorithms for low boom and low drag supersonic aircraft conceptual design. And the approximate response surface models of sonic boom and aerodynamics are replaced by direct linearized analysis, which have more fidelity in multidiscipline optimization. A conceptual supersonic aircraft design environment (CSADE) will be constructed based on those methods.

2. Low boom and low drag supersonic aircraft design method

SGD method is developed by Seebass.[13] SGD method is based on linearized supersonic flow theory, which provides sonic boom minimizing equivalent area distributions under the supersonic cruise condition described. The F function of SGD method can be obtained by Eq. (1). And Fig. 1 is the illustration of F function of SGD method.

$$F(x)=\begin{cases} 2xH/y_{\mathrm{f}} & (0 \leq x < y_{\mathrm{f}}/2) \\ C(2x/y_{\mathrm{f}}-1)-H(2x/y_{\mathrm{f}}-2) & (y_{\mathrm{f}}/2 \leq x < y_{\mathrm{f}}) \\ S_l(x-y_{\mathrm{f}})+C & (y_{\mathrm{f}} \leq x < \lambda) \\ S_l(x-y_{\mathrm{f}})-D & (\lambda \leq x < l) \end{cases} \tag{1}$$

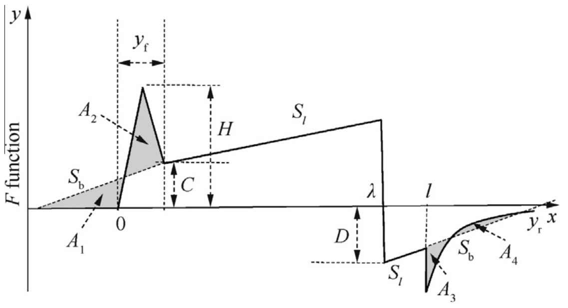

Fig. 1 F function based on SGD method.

where y_{f} is the nose bluntness; x the axis coordinate; S_l the F function slope; S_{b} the slope of balance line in F function; y_{r} the position of rear area balancing; l the length of aircraft and C, D, H are parameters of F function which are illustrated in Fig. 1.

The F function after of the aircraft expressed in terms of the F function over the aircraft's length is given by Eq. (2).

$$F(x)=\frac{-1}{\pi(x-l)^{1/2}}\int_0^l \frac{(l-\xi)}{x-\xi}F(\xi)\mathrm{d}\xi \qquad (y>l) \tag{2}$$

The parameters of F function have significant effect on ground sonic boom and drag. Fig. 2 illustrates the relationship between the F function slope and the shape of ground sonic boom wave. Δp is sonic boom overpressure. It can be found that if slope $S_l > 0$, the sonic boom maximum pressure is larger than initial overpressure; on the other hand, if slope $S_l \leqslant 0$, the sonic boom maximum pressure is equal with initial overpressure.

Fig. 3 shows the relationship of F function slope, sonic boom maximum pressure and wave drag coefficient $C_{D\mathrm{W}}$. The left ordinate is wave drag coefficient and right ordinate is sonic boom maximum pressure. It can be found that with the increase of F function slope, wave drag coefficient decreases. But sonic boom maximum pressure decreases first, then increases.

Fig. 4 shows the relationship between nose bluntness, sonic boom maximum pressure and wave drag coefficient. It can be found that with the increase of y_{f}, wave drag coefficient decreases and sonic boom maximum pressure increases.

Because wave drag is an important component of supersonic aircraft's drag, wave drag coefficient is an optimization object. On the other hand, perceived loudness in decibels (PLdB) is sensitive to sonic boom rise time, and the sonic boom prediction method is based on waveform parameter method which cannot predict rise time accurately, and sonic boom maximum pressure is used in optimization.[14] The optimization of the sonic boom maximum pressure and wave drag coefficient has significant value in supersonic aircraft design.

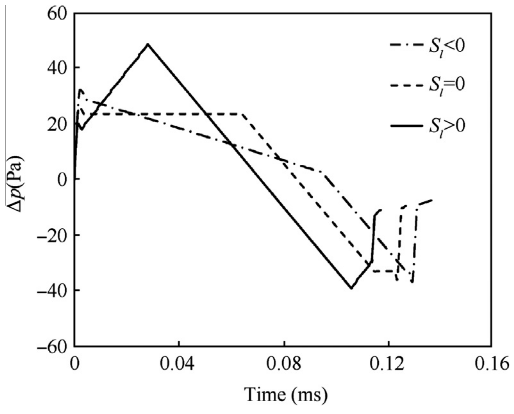

Fig. 2 Relationship between the F function slope and the shape of ground sonic boom wave.

3. Conceptual supersonic aircraft design environment

A conceptual supersonic aircraft design environment (CSADE) is constructed, for the purpose of mitigating sonic boom level and reducing wave drag coefficient. The