3) A centerbody on the flat-plate models had little effect on the lift coefficient and did not produce better agreement with the three-dimensional model than the flat-plate model alone.

4) Caution should be exercised when attempting to apply results and overall trends from flat-plate, swept-wing models to three-dimensional models and full-scale aircraft.

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Assessment of Simultaneous Perturbation Stochastic Approximation Method for Wing Design Optimization

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Introduction

THE need for addressing optimization problems that are characterized by the presence of a large number of design variables, complex constraints, and discrete design parameter values exists in many fields including engineering design. A variety of local and global optimization algorithms have been developed for addressing such problems. Besides deterministic methods, stochastic methods such as genetic algorithm (GA) and simulated annealing (SA) algorithm have recently found applications in many practical engineering design optimization problems. These algorithms are easily implemented in robust computer codes as compared with deterministic methods because they do not depend on direct gradient information, which most deterministic methods do. However, SA and GA methods require a large number of function evaluations and relatively longer computation time than deterministic methods, especially in the case of complex design problems. Although the use of parallel GA and parallel SA as outlined in Wang and Damodaran[1] offers a way to reduce the large computational time, an attractive alternative to SA and GA could be the simultaneous perturbation stochastic approximation (SPSA) method described in Spall.[2] The SPSA method has been applied to numerous difficult multivariate optimization problems in many diverse areas such as statistical parameter estimation, feedback control, simulation-based optimization, signal and image processing, and experimental design. The essential feature of SPSA, which accounts for its power and relative ease of implementation, is the underlying gradient approximation, which requires only two measurements of the objective function regardless of the dimensions of the optimization problem. This feature allows for a significant decrease in the cost of optimization, especially for problems with a large number of variables to be optimized.

The aim of this Note is to compare performance of SPSA with SA and GA and to explore any advantages that SPSA might offer to overcome the large computational efforts of SA and GA when applied to wing-design problems. These methods are briefly outlined following the statement of the wing-design optimization problem, which will form the application problem to assess and compare the performance of SPSA in relation to SA and GA.

Wing-Design Problem

The application concerns the design of wing shape such that the aerodynamic efficiency of the wing or the lift L to drag D ratio reaches a maximum value during cruise with the wing weight acting as a constraint, that is, the goal is to determine the wing geometry by either minimizing D/L or maximizing L/D with the wing weight as a constraint. The D/L ratio can be formulated in detail using the analytic formulas for aerodynamic analysis as defined in Raymer.[3] The lift L is defined as $L = C_L q S$, where $q = \frac{1}{2}\rho V^2$ is the dynamic pressure, ρ is the density of air, V is the flight speed, $C_L = C_{L\alpha}\alpha$ is the the lift coefficient where α is the angle of attack and $C_{L\alpha} = 2\pi A_R/\{2+\sqrt{[4+(A_R\beta/\eta)^2(1+\tan^2\lambda/\beta^2)]}\}$ is the lift curve slope. In the expression for lift curve slope, $A_R(=b^2/S)$ is the wing aspect ratio, where b is the wing span, λ is the wing sweep angle, η (value of which lies in the range 0.95–1.0) is the airfoil efficiency factor, $\beta = 1 - M^2$ is the compressibility factor, and M is the Mach number. The total drag is defined as $D = C_D q S$, where the total drag coefficient is $C_D = C_{\mathrm{Di}} + C_{D0}$, which consists of the induced drag coefficient $C_{\mathrm{Di}} = C_L^2/(\pi A_R e)$ and the zero-lift drag coefficient $C_{D0} = C_f F Q$. In these expressions $e = 4.61(1 - 0.045A_R^{0.68})(\cos\lambda)^{0.15} - 3.1$ is the wing planform efficiency factor, $C_f = 0.455/[(\log_{10} Re)^{2.58}(1+0.144M^2)^{0.65}]$ is the surface skin-friction coefficient, which is a function of the Reynolds number Re, $F = \{1 + [0.6/(x/c)_m](t/c) + 100(t/c)^4\}[1.34M^{0.18}(\cos\lambda)^{0.28}]$ in which t/c is the airfoil thickness-to-chord ratio, $(x/c)_m$ is the chord-wise location of the maximum thickness-to-chord ratio, taken as 0.3 in the present study, and Q is a factor accounting for interference effects on drag taken as 1.0 in the present study. The weight of the wing (in pounds) is $W_{\mathrm{wing}} = 0.0106(W_{\mathrm{dg}}N_z)^{0.5}S^{0.622}A_R^{0.75}(t/c)^{-0.4}(\cos\lambda)^{-1}$, where W_{dg} is the design gross weight in pounds and N_z is the ultimate load factor, which is assumed to be 13.5 for subsonic flow.

The design variables for the wing design optimization, that is, α, b, c, λ, and W_{wing}, represent the angle of attack, wing span, mean aerodynamic chord, sweep angle, and wing weight, respectively. The objective function to be optimized is $F(X) = D/L$ and is defined as follows:

$$\text{Minimize } F(X) \tag{1}$$

subject to six constraints on the design variables defined as follows:

$$\begin{aligned} &1.0\,\text{deg} \le \alpha \le 10.0\,\text{deg}, && 10.0 \le b \le 50.0 \\ &3.5 \le c \le 10.0, && 0.0\,\text{deg} \le \lambda \le 35.0\,\text{deg} \\ &0.5 \le A_R \le 15.0, && W_{\mathrm{wing}} \le 2473\ \text{(lb)} \end{aligned} \tag{2}$$

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Table 1 Comparison of optimal results from SA, GA, and SPSA

Algorithm	α, deg	b, ft	c, ft	λ, deg	W, lb	D/L	NFE
SPSA	3.432	44.994	5.986	18.115	2443.93	0.0319	1,149
GA	3.199	43.861	4.955	19.912	2444.03	0.0324	13,040
SA	3.199	44.987	5.947	18.002	2443.93	0.0319	9,601

An external penalty function method is used to incorporate the constraints so that the composite function to be minimized can be defined as

$$F(X) = \frac{D}{L} + \sum \max(0, g_j)^2 \tag{3}$$

where X is the vector of the six design variables and the design constraints $g_j(X) \leq 0$, which are represented as inequality constraints.

Optimization Algorithms

The optimization algorithms used in this study are stochastic global search methods. SPSA is relatively easy to implement and does not require gradient information. It is a fairly robust method and has the ability to find a global minimum when multiple minima exist. SPSA is an algorithm that is based on a "simultaneous perturbation" gradient approximation. The simultaneous perturbation approximation uses only two function measurements independent of the number of parameters (say, p) being optimized. The SPSA algorithm works by iterating from an initial guess of the optimal vector X_0. First, the counter index k is initialized to a value of 0, an initial guess of the design variable vector X_k is made, and nonnegative empirical coefficients are set. Next a p-dimensional random simultaneous perturbation vector Δ_k is constructed, and two measurements of the objective function, namely, $g(X_k + c_k \Delta_k)$ and $g(X_k - c_k \Delta_k)$, are obtained based on the simultaneous perturbation around the given vector X_k. The parameter $c_k = c_0/(k^m)$, where c_0 is a small positive number taken as 0.01 in this study, k is the loop index, and m is a coefficient taken as $\frac{1}{6}$ in this study. The term Δ_k represents the random perturbation vector generated by Monte–Carlo approaches, and the components of this perturbation are independently generated from a zero-mean probability distribution; a simple distribution that has been used in this study is the Bernoulli ± 1 distribution with probability of $\frac{1}{2}$ for each of the ± 1 outcome. This is followed immediately by the calculation of the gradient approximation based on two measurements of the function based on the simultaneous perturbation around the current value of the design variable vector and the updating of the design vector X_k to a new value X_{k+1} using standard SA form. Finally the algorithm is terminated when insignificant changes in several successive iterations occur or if the maximum allowable number of iterations has been reached. The details of the step-by-step implementation of the SPSA algorithm can be found in Spall.[4,5] The SA method used is described in Deb.[6] For this problem SA is implemented by setting the initial temperature to 5, and the cooling schedule is algebraic of the form $T_{k+1} = \gamma T_k$, where γ takes a value of 0.5. The GA method used in this study is outlined in Deb[6] and essentially follows the method in Goldberg.[7] For this problem GA method is implemented with a population size of 80; a crossover probability of 0.90 and mutation probability of 0.05 have been used to arrive at optimal values.

Results and Discussions

For the wing-design optimization problem the values of the parameters used are $M = 0.7$, $t/c = 0.12$, $Q = 1.0$, $(x/c)_m = 0.3$, and $\eta = 0.95$, and the same termination criterion $|f(x_{k+1}) - f(x_k)| \leq 10^{-6}$ was used to terminate the optimization methods. Table 1 shows the optimum values of the objective function and design variables reached by the two optimization algorithms. In this table NFE refers to the number of function evaluations required to reach the global minima. Figure 1 shows the variation of the objection function with the number of function evaluations required using the SPSA method to reach the optimal value. It also shows the variation of the computed objective function (D/L) with wing weight. Figure 2 shows

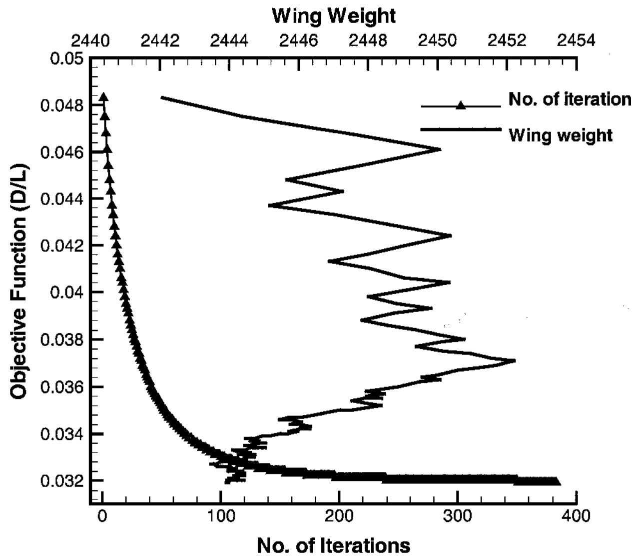

Fig. 1 Convergence of objective function vs design iterations and the variation of objective function vs wing weight toward global optimal values.

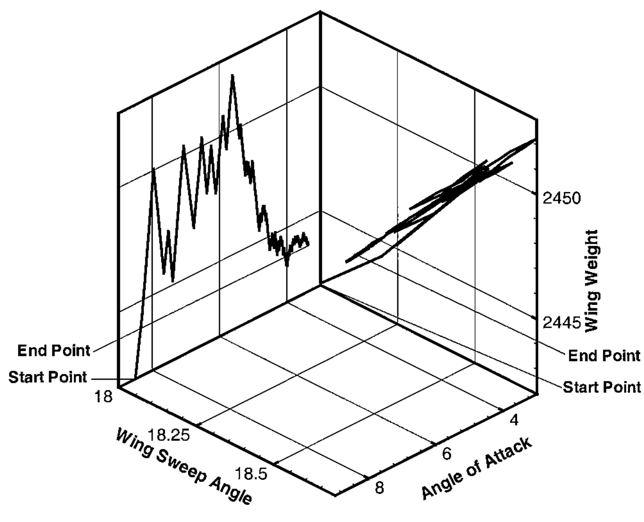

Fig. 2 Projected routes of design variables angle of attack α and sweep angle λ vs wing weight toward the global optimal values.

the variation of angle of attack and wing sweep with wing weight. It can be seen that the optimal values of the objective function and design variables subject to the same constraints from SA and GA are very similar to those attained by SPSA. It can be seen that SPSA attained optimal design values in 383 iteration steps, that is, 1149 measurements of objective function. At the same time GA took more than 13,000 iterations, and SA took more than 9,000 iterations to reach the optimal results. The SPSA method is a significantly faster method than either GA or SA as a global optimization method for this wing-design problem and can serve as a potential cost effective stochastic global optimization design tool than either SA or GA for similar classes of design problems.

Conclusion

A wing-design optimization problem was performed using SPSA, SA, and GA methods in this study. It can be seen that SPSA is more efficient than SA and is also relatively easy to implement. SPSA requires only two measurements of the objective function regardless of the dimensions of the design space corresponding to the optimization problem and the cost of optimization decreases. Although SA and GA can avoid getting trapped in local optima, they require a large number of function evaluations and a long computation time to reach the optima. Future work to assess the performance of SPSA for constrained and unconstrained aerodynamic shape design studies will be carried out in the near future to establish the cost benefits and to investigate the extent to which SPSA offers comparative advantages over GA or SA for aerodynamic design optimization problems.

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Lift Augmentation of a Low-Aspect-Ratio Thick Wing in Ground Effect

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Nomenclature

C_D	=	coefficient of drag
C_L	=	coefficient of lift
C_L/C_D	=	lift-to-drag ratio
C_{MLE}	=	coefficient of pitching moment about leading edge
c	=	chord length
h	=	true ground clearance
Re	=	Reynolds number
x_{CP}	=	center of pressure measured from wing leading edge
α	=	angle of incidence
ε	=	total solid and blockage correction factor

Introduction

IT is well known that in close proximity to the ground the aerodynamic characteristics of a wing change considerably, something that has come to be known as wing in ground effect. There have been several numerical studies to model the aerodynamic characteristics of airfoils under ground effect,[1–3] but reliable experimental data are somewhat limited.[4] Ground effect is important because it can modify the aerodynamic performance of an aircraft during landing and takeoff. It assumes even a greater importance in the design and operation of aircrafts that take off from and land on water and cruise in proximity to the water surface such as the wing-in-ground vehicles. Another possible application of such study lies in the design of naval vessel such as the high-speed catamaran where the vessel can be conceived to be a wing body at very low angle of incidence, and end plates extending beyond the wing bottom surface are used to represent its hulls. The aerodynamic lift would support part of the weight of the vessel and thus decrease the hydrodynamic drag by reducing the wetted area of the hulls. The aspect ratio of such a wing representing a high-speed marine vessel would, however, be low. Additional fixed angled flaps could, therefore, be used to boost the production of lift. With these considerations a wind-tunnel investigation of lift augmentation of a low-aspect-ratio wing of high thickness-to-chord ratio at a very low angle of incidence using ground effect, flaps and end plates was, therefore, carried out.

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Experiment

Initial Considerations

The Reynolds number Re for a catamaran (for example, the AMD K50 Sunflower) of length of approximately 80 m and operating at a speed of around 50 kn is about 1.35×10^8. Experimental and numerical studies[4,5] show that above Re of 3.2×10^5, the aerodynamic performance characteristics of wing under ground effect remain virtually unchanged if the angle of attack is kept below 5 deg. A 1:50 scale model at a speed of 40 m/s and tested below angle of incidence 5 deg would give the test R_N a value of around 3.6×10^6 for this study. This value was chosen for wind-tunnel testing to avoid Reynolds-number effect in the performance between the model and the full size of the craft.

Assuming a vessel clearance of 2 m from the water and again using the 1:50 scale, the minimum length with which the end plates under zero-deg flap condition could be extended was found to be 40 mm. The design of a ground board was considered necessary to represent a calm horizontal surface. Also, for aircrafts flaps are generally 20–40% of chord length, and they can operate at very high flap angles, 60 deg for example, and for short durations, usually during takeoff or landing. For this study, therefore, the flap length was considered to be much less than those used in aircrafts. Thus, taking a flap length of 12.5% of chord requires a flap of 168.75 mm in length, which was rounded off to 170 mm. This, along with 40-mm clearance for water surface gave a flap angle of 13.2 deg. A 0–10-deg range of flap angle was, therefore, considered adequate for this study.

Test Facility

The 1270 × 915-mm closed-circuit wind tunnel fitted with a six-component balance of the aerodynamics laboratory of the University of New South Wales was used in the tests. The wind tunnel has a velocity range of 0–70 m/s and a turbulence intensity of 0.2%. A pitot-static tube with a Betz manometer was used to record the wind-tunnel speed upstream of the test model. Force and moment measurements from strain gauges were obtained from digital display on the control panel of the wind tunnel.

Test Model

The upper surface cross-sectional profile of the wing body was generated through a consideration of a modified deck arrangements of an existing commercial high-speed catamaran while keeping the bottom surface flat. The top and middle decks were moved forward so that the maximum camber was obtained at 25% of chord from the leading edge. A schematic of this process is shown in Fig. 1. Using 1:50 scale, the chord, span, and height dimensions of the wing were worked out to be 1350, 180, and 230 mm, respectively. The maximum thickness-to-chord and aspect ratios of this wing then became 0.17 and 0.13, respectively.

The wing body was designed using the modeling package CATIA, and then NC milling codes were generated from CATIA facility. The