



Genetic algorithms for optimal series propeller design

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Abstract

A genetic algorithms (GA) technique is employed to determine a set of design parameters, which maximize efficiency of B-series propeller with nonlinear constraints. This is the first-known application of the genetic algorithms technique for optimal nonlinear series propeller design. GA are powerful and broadly applicable stochastic search and robust optimization techniques which follow the Darwinian principle of "survival of the fittest". GA are very suitable for large parameter space search such as propeller design. Real-world design cases are used to demonstrate that the proposed GA method can be successfully applied to optimal B-series propeller design.



1. Introduction

Today, computer-aided design programs assist designers get the goal of optimal efficiency with regards to propeller design problems. Reich [1] demonstrated that propeller design is an iterative process, which aims to optimize the efficiency of a propeller subject to some design constraints, which may conflict with one another. Traditionally, propeller design task is completed on the base of design charts. The design process was performed manually. In recent years, artificial intelligence (AI) research has provided designers with computer tools that can emulate the decision-making behavior of experienced designers. Expert system and genetic algorithms are two main aspects of AI that have been well developed for assisting designers. A knowledge-based system simulates designers' intelligence in specific domains, such as propeller design [2]. In order to improve the knowledge dependence, manual selection and iterative design process of such system, we attempt to use genetic algorithms technique to optimize efficiency of B-series propeller.

This paper demonstrates the first-known application of the GA technique for optimal nonlinear B-series propeller design. We focus on the principal parameters in B-series propeller performance. There are several geometry parameters like the propeller diameter D , the pitch ratio P/D , the expanded area ratio A_E/A_o , the engine delivered power P_D , the propeller thrust T , the RPS of propeller n and the advanced velocity of propeller V_A . The objective of optimization is to maximize the efficiency of B-series propeller. The constraint for cavitation avoidance and other design constraints such as given diameter D or given RPS n are also considered in our optimization process.

2. B-series propeller design

The open water test data of B-series propeller are refereed to G. Kuiper [3]. Results therein are given in the non-dimensional open water representation, in



which the thrust coefficient K_T and the torque coefficient K_Q are plotted against the advance ratio J . The definitions of these coefficient are

$$J = \frac{V_A}{nD} \quad (1)$$

$$K_T = \frac{T}{\rho n^2 D^4} \quad (2)$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \quad (3)$$

The open water efficiency of propeller η is defined as the ratio of thrust power $P_T = TV_A$ and the power delivered to the propeller $P_D = 2\pi nQ$.

$$\eta = \frac{TV_A}{2\pi nQ} = \frac{K_T J}{K_Q 2\pi} \quad (4)$$

By regression analysis, the open water diagram of the B-series propeller can be reduced to two polynomial of the following form for a Reynolds number of $2 \cdot 10^6$ [4]:

$$K_Q = \sum_{n=1}^{47} C_n (J)^{s_n} \left(\frac{P}{D}\right)^{t_n} \left(\frac{A_E}{A_O}\right)^{u_n} (Z)^{v_n} \quad (5)$$

$$K_T = \sum_{n=1}^{39} C_n (J)^{s_n} \left(\frac{P}{D}\right)^{t_n} \left(\frac{A_E}{A_O}\right)^{u_n} (Z)^{v_n} \quad (6)$$

where the coefficients C_n , s_n , t_n , u_n , and v_n can be taken from [4].

The required bladed area ratio according Keller's formula is given by

$$EAR = \frac{(1.3 + 0.3Z)T}{(P_o - P_v)D^2} + k \quad (7)$$

where the pressure P_o is the static pressure at the propeller shaft, and P_v is the vapor pressure of water. The value of k is zero for ships with a smooth wake

distribution such as naval ships, and 0.2 for single screw ships [3].

3. Genetic algorithms

The GA were first developed by John Holland [5] in the early 1970s. As GA evolve, the genetic operators, such as reproduction, crossover and mutation, are applied to create new populations. After a number of generations, this evolutionary process will lead to a population of highly fit individuals. The fittest individual of the final generation should be an optimal solution. The logic flowchart is presented in Figure 1.

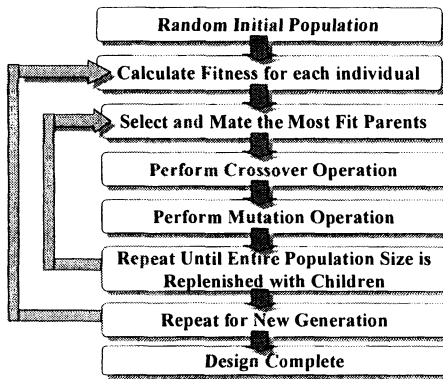


Figure 1: The logic flowchart of genetic algorithms.

The most important GA parameters are population size, crossover probability and mutation probability, selection strategy and generation gap [6]. The GA parameters used in this paper are listed in Table 1.

Population Number	100
Probability of Crossover	0.6
Probability of Mutation	0.01

Table 1: GA parameter for optimal B-series propeller design.



Several strategies have been proposed to handle constraints with GA [7], the penalty strategy is preferred in our GA method because it can be easily combined within objection functions.

4. Application of GA to optimal B-series propeller design

We use several real world design cases to illustrate the results of the proposed GA method. The design cases are presented in Table 2.

Case No.	Design Condition (Given parameters)			Optimal Design Search Parameters (Unknown parameters)			
	n	VA	PD	P/D	D	T	AE/AO
1	n	VA	PD	P/D	D	T	AE/AO
2	D	VA	PD	P/D	n	T	AE/AO
3	n	VA	T	P/D	D	PD	AE/AO
4	D	VA	T	P/D	n	PD	AE/AO

Table 2: B-series propeller optimal design cases.

The GA parameter search space for optimal B-series propeller designs are shown in Table 3. Note that the pitch ratio and expanded area ratio cover the all B-series propeller corresponding data range, and the diameter and RPS of propeller cover a reasonable range of designs.

Parameter	Design Range	Resolution	Bit
P/D	0.5 ~ 1.4	0.028	5
D	0.5 ~ 10.0	0.297	5
AE/AO	0.45 ~ 1.05	0.019	5
n	100 ~ 1000	28.125	5

Table 3: GA parameter search space for optimal B-series propeller designs.

It is quite common to start the real-world design from the available engine power. The engine will develop a certain power at a given revolution rate. The number of blade is five. The given parameters are : $n = 720$ 1/min., $VA = 14.42$



m/sec and PD = 440 kW.

We define the optimization problem in case 1 as follows:

$$\text{Maximize } \eta = \frac{K_T J}{K_Q 2\pi}$$

with the following constraints:

$$g_1 = \frac{A_E}{A_O} - \left[\frac{(1.3 + 0.3Z)K_T \rho n^2 D^4}{(P_O - P_v)D^2} + k \right] \geq 0 \quad (8)$$

$$1.6 \geq K_T \geq 0 \quad (9)$$

$$1.6 \geq 10 * K_Q \geq 0 \quad (10)$$

$$h_1 = x_1 - n = 0 \quad (11)$$

$$h_2 = x_2 - V_A = 0 \quad (12)$$

$$h_3 = x_3 - P_D = 0 \quad (13)$$

Equation (8) is used to avoid the cavitation based on the Keller's formula. Equations (9) and (10) are inequality constraints for K_T and K_Q represented by the (5) and (6). This is due to the consideration that negative or large values of K_T and K_Q occurring in the GA search may lead to infeasible design results. The three equality constraints in equations (11), (12) and (13) are introduced for the given parameters (fixed values) in this design case. All the six constraints are combined into a single fitness function with certain penalties. The optimization process takes five seconds on AMD K6-350 CPU PC using 50 generations with 100 individuals. It is very efficient in terms of time and cost by using the GA method. The results shown that GA method had found the optimal parameters for B-series propeller in design case 1. For comparison, the propeller parameters obtained by GA and by the iteration method used by [3] are listed below:

Method	P/D	D	A_E/A_O	J	K_T	K_Q	Efficiency	Thrust (N)
GA optimization	1.400	1.01	0.644	1.190	0.158	0.040	0.751	24,300
Iteration optimization	1.400	1.01	0.750	1.190	0.153	0.0387	0.747	23,500

It shows that a small improvement in the efficiency and an about 3.5% increase in the thrust from the present GA method. Figure 2 shows the optimization history of efficiency of the best in generation. It can be seen that efficiency reached the optimal solution at the sixth generation, and converged at 0.751 in the evolution history.

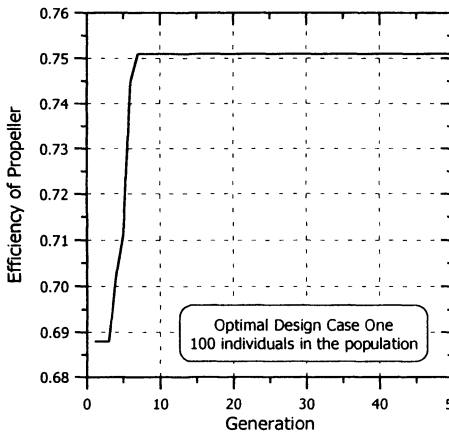


Figure 2: Optimization history of efficiency of the best in case 1.

Case 1 is similar to case 2. The only difference is that in case 2 the diameter is given and the optimal rate of rotation is to be selected by GA. The given parameters are : diameter = 1.01 m, $V_A = 14.42$ m/sec and $P_D = 440$ kW. The number of blade is five. In the same manner as case one, the optimal results are shown below:

GA	P/D	n	A_E/A_O	J	K_T	K_Q	Efficiency	Thrust (N)
optimization	1.371	742.19	0.663	1.154	0.160	0.039	0.745	26,057



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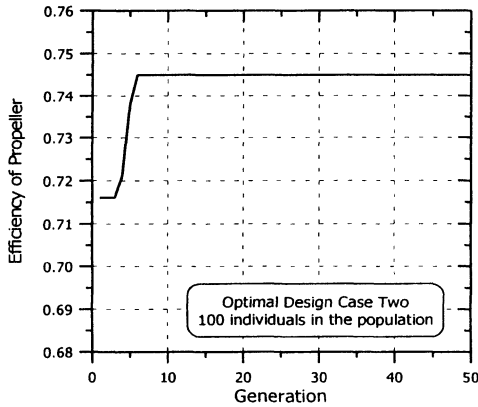


Figure 3: Optimization history of efficiency of the best in case 2.

Case 3 is used to optimize the diameter for a given rotation rate. The given parameters are: $n = 106$ 1/min, $V_A = 8.65$ m/sec and $T = 1,393.02$ kN. The number of blade is four. The comparison between the GA and iteration method is presented below:

Method	P/D	D	A_E/A_O	J	K_T	K_Q	Efficiency
GA optimization	0.906	7.355	0.589	0.666	0.150	0.024	0.655
Iteration optimization	0.9	7.36	0.55	0.665	0.148	0.0239	0.656

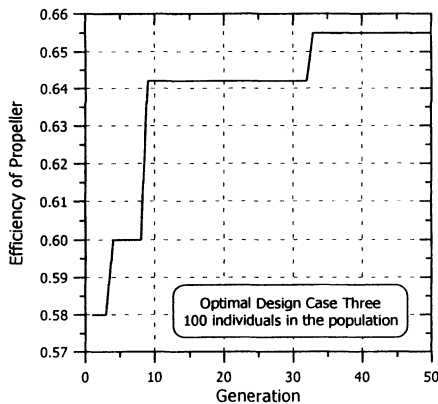


Figure 4: Optimization history of efficiency of the best in case 3.

Case 4 aims to design the optimal rotation rate for a given propeller diameter. The given parameters are : $D = 7.0$ m, $V_A = 8.65$ m/sec and $T = 1,393.02$ kN. The number of blade is four. The comparison between the GA and iteration method is presented below:

Method	P/D	n	A_E/A_0	J	K_T	K_Q	Efficiency
GA optimization	0.994	106.45	0.498	0.697	0.18	0.031	0.652
Iteration optimization	1.0	106	0.55	0.699	0.181	0.031	0.651

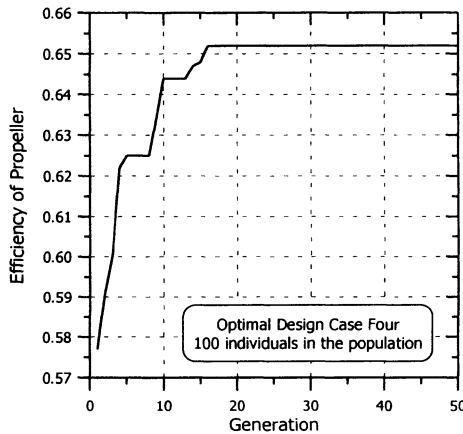


Figure 5: Optimization history of efficiency of the best in case 4.

5. Conclusion

This paper deals with the application of genetic algorithms for optimal B-series propeller design with nonlinear constraints. The proposed method evolves feasible design parameters by performing the adaptive search of possible parameter space. The GA method achieves higher efficiency than the iteration method, and doesn't needs experienced designer in choosing the proper initial values of the unknown design parameters in order to ensure a realistic and



practical solution. Further, the GA method allow a search in larger parameter space than the conventional method and obtains more reliable results.

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