Title:

Cost Based, Integrated Design Optimization using a Parametric CAD Model

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Abstract:

This paper present a novel approach for developing a decision support tool for designers based on manufacturing cost. The approach focuses on exploiting the advantages offered by integrating parametric CAD, manufacturing processing time based cost estimation and optimization technique within an integrated framework. The methodology is then applied in optimizing the geometry for minimum manufacturing cost of rotor blade.

Introduction:

Today advanced composite rotor blades are widely used in modern helicopters. Blade construction is changed with the aerodynamic section that is fabricated from metal to composites. The design of composite rotor blades can be one of the most challenging tasks because of the sophisticated geometry changes in chord, twist, airfoils, length of the blade and tip shapes [1]. Better designs may also be produced if designers could evaluate the cost implications of their design parameters/factors in the early design process. Design for Manufacturing (DFM) is a strategy frequently used by manufacturers to reach a manufacturing cost reduction through design optimization. Previous studies showed that over 70% of the production cost of a product is determined during the conceptual design stage [2]. Cost reduction before the production process can be achieved by evaluation of the numerous trade-off scenarios related to product design, material choice, process performance and investment requirements. Design optimization is an important engineering design activity. Research on design optimization has considered better solution methods as well as novel formulations. Computer-aided design tools such as CATIA, UGS NX and Pro-Engineer can be used by engineers to experiment with part definitions leading to optimal design. However, they could not access the impact of design on manufacturing cost. Many tasks the designer has to do, can be automatized. But the current CAD systems does not offer all needed functionalities [3]. A focus is to exploit the advantages offered by combining parametric CAD and manufacturing process parameters and to do design optimization study. Authors [4-5] developed the process based cost model and integrated approaches for manufacturing cost estimate of composite rotor blade at the conceptual design stage, have been discussed. However, cost based design optimization has not been discussed.

This paper describes the construction of a system which overcomes the above issues by presenting a quantitative methodology for evaluating trade-offs between the processing time for manufacturing processes, manufacturing cost, a parametric CAD model and an optimizer concurrently to evaluate various designs.

Main Idea:

The idea of manufacturing cost reduction through design optimization is to make money and reduce the overhead. Cost reduction before the production process can be achieved by evaluation of the

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numerous trade-off scenarios related to product design, material choice, process performance and investment requirements. Keeping the manufacturing process simple, reducing the costs of materials and increasing the efficiency of the manufacturing process are the best ways to do this. Fig. 1 shows the overview of the proposed cost based design optimization methodology. First, we present an overview of the process followed by an explanation on the role of geometry parameterization, manufacturing processing time estimation, manufacturing cost and systems performance evaluation. This section also briefly describes the various software tools used for the functions listed in the proposed methodology.

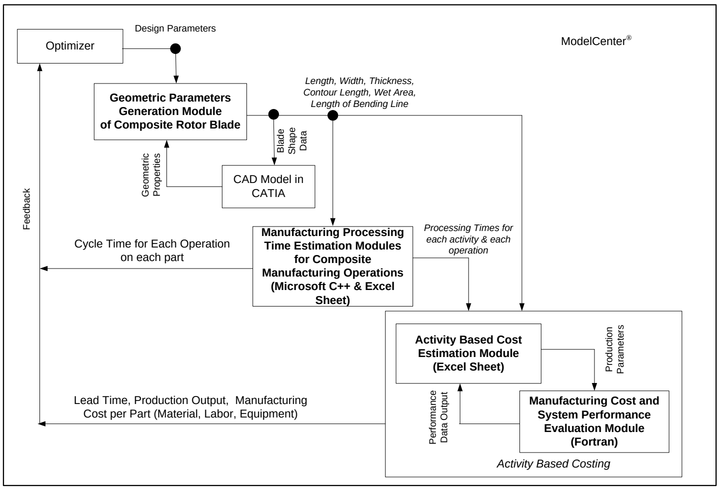


Fig. 1: An overview of the proposed cost based design optimization methodology.

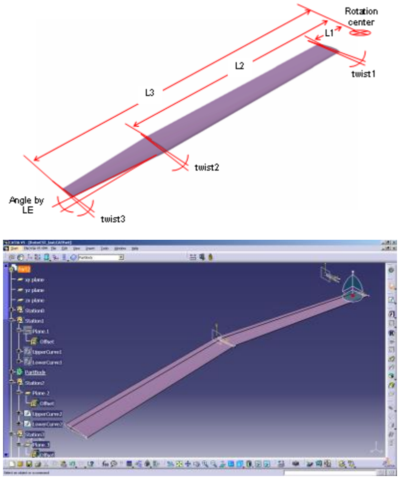


Fig. 2: Main geometrical and planform parameters of the blade surface.

Overview of the Process Sequence:

The five essential elements to the process used here are: (i) geometric parameters generation module (ii) manufacturing processing time estimation module (iii) manufacturing cost estimation module (iv) manufacturing system performance evaluation module and (v) a robust optimizer to provide the inputs to the parametric CAD model while simultaneously validating the cost values against the formulated problem. The developments of modules are explained details by authors in [3] [4] [8] [9]. Fig. 1 shows the integrated framework and flow of data in the process. The optimizer drives the entire process by feeding a set of input parameters to the parametric solid model within a CAD tool. The output data of modified geometry is then passed on the manufacturing processing time estimation module. The output data of manufacturing processing time module is then passed on to the manufacturing cost and system performance evaluation module. The optimizer receives and optimize with the output data of manufacturing cost and system performance evaluation module. The calculated costs are then passed back to the optimizer. The optimizer uses a specified algorithm to calculate the input parameters for the subsequent iteration by comparing the cost output against the objective and constraint functions. This process is continued iteratively evaluating numerous candidate geometries until the optimum design solution is found.

Shape Configuration and Parametric model generation in CATIA®

Computer Aided Design (CAD) Parametric model for rotor blade

Blade 3D surface and solid geometries are defined parametrically and modelled in CATIA V5. The input parameters of blade surface: airfoil coefficients (AU0, AU4, AL0, AL4), and planform parameters:

spanwise distances (L1, L2, L3), chord length, twist and tip sweep angle (by leading edge) are shown in Fig. 2.

The Class function/Shape function Transformations method (CST)

The blade surface represented with lofting by three airfoil cross sections. The Class function/Shape function Transformations method (CST) has been used for airfoil representation. The CST method is based on analytical expressions to represent and modify the various shapes [6]. The components of those are shape function and class function. The shape function provides the ability to directly control the key parameters of the geometry.

By using the CST method, the curve ordinates are distributed by the following equation:

$$y(x/c) = C_{N2}^{N1}(x/c)\cdot S(x/c)$$ where

$$C_{N1}^{N2}(x/c) = (x/c)^{N1}(1-x/c)^{N2}$$:class function, $$S(x/c) = \sum_{i=0}^{N}\left[A_i.(x/c)^i\right]$$: shape function

N1, N2: exponents

x: non-dimensional values from 0 to 1.

c: curve length

Bernstein polynomials are used as shape functions.

$$S_i(x) = K_i x^i (1-x)^{n-i}$$ where $$K \equiv \binom{n}{i} = \frac{n!}{i!(n-i)!}$$: binomial coefficients

n: order of Bernstein polynomial

i: numbers 0 to n

In this study, NACA 0012 is chosen as an airfoil baseline. With the given data coordinate points in Cartesian coordinate space, a curve fit is generated using 4th order Bernstein polynomials. The Class function for the airfoil [7] [8] [9]:

$$C(x) = x^{0.5}(1-x)$$

Airfoil distribution function defined as upper curve and lower curve are presented below.

$$y_l(x) = C(x)\begin{bmatrix} A_{lo}(1-x)^4 + A_{l1}4x(1-x)^3 + A_{l2}6x^2(1-x)^2 \\ +A_{l3}4x^3(1-x) + A_{l4}x^4 \end{bmatrix}$$ $$y_u(x) = C(x)\begin{bmatrix} A_{uo}(1-x)^4 + A_{u1}4x(1-x)^3 + A_{u2}6x^2(1-x)^2 \\ +A_{u3}4x^3(1-x) + A_{u4}x^4 \end{bmatrix}$$

Where: Au0 = 0.1718; Au1 = 0.15; Au2 = 0.1624; Au3 = 0.1211; Au4 = 0.1671; Al0 = -0.1718; Al1 = -0.15; Al2 = -0.1624; Al3 = -0.1211; Al4 = -0.1671.

Fig. 3 shows the representation procedure based on the CST method [7]. The input and output data flow of Geometric Parameters Generation Module is shown in Fig. 4.

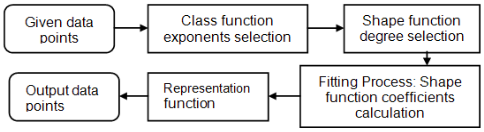


Fig. 3: Representation procedure based on CST method.

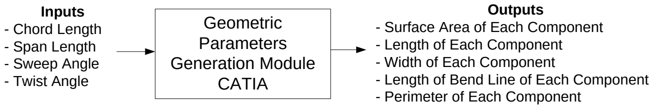


Fig. 4: Input-Output data of Geometric Parameters Generation Module

Time Estimation, Manufacturing Cost and Manufacturing System Performance Evaluation Modules:

The manufacturing flow for aerospace advanced composite manufacturing is shown in Fig. 5. The developments of time estimation module, manufacturing cost and manufacturing system performance evaluation modules have been discussed by author [3-4].

Optimizer:

Genetic algorithm (GA) is used as optimization method for this study. Basics of the algorithm are that decisions make in most computational steps of the algorithm are based on random number generation. The algorithms use only the function values in the search process to make progress toward a solution without regard to how the functions are evaluated. The integrated framework shown in Fig. 6 uses ModelCenter® to integrate for implemented modules mentioned earlier. ModelCenter® controls input data, execute analysis, and retrieve output data. By automating and simplifying these tasks, ModelCenter® makes the design process more efficient, saves engineering time, and reduces the chances for error in the design process.

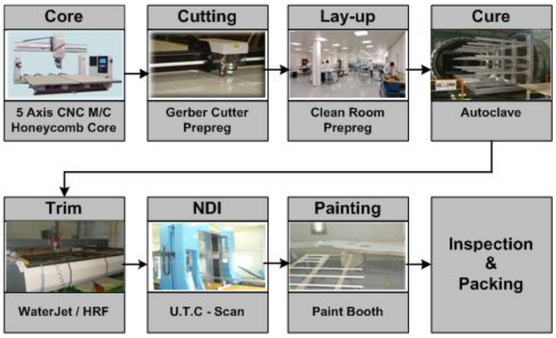


Fig. 5: Manufacturing flow for aerospace advanced composite manufacturing.

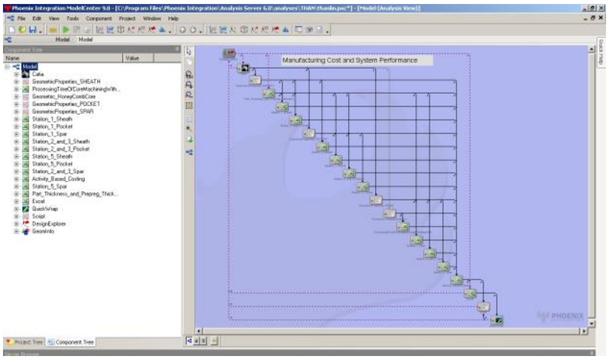


Fig. 6: Integrated Model for Design Optimization.

Optimization Formulation:

Design Variables

The design variables are maximum pretwist, taper ratio, point of taper initiation, blade root chord, A_0 to A_4 coefficients of airfoil distribution function. The blade is rectangular to station of the point of taper initiation and then tapered linearly to the tip. The twist varies linearly from the root to the tip. NACA0012 was chosen as baseline airfoil.

Constraints

The requirements are the followings:

- Production output rate per year
- Blade Surface Area

Objective function

Manufacturing cost and system performance evaluation module provides the objective function to reduce the manufacturing cost of a composite rotor blade.

To minimize

Manufacturing Cost of a composite blade, $C_P = C_M + C_L + C_E$

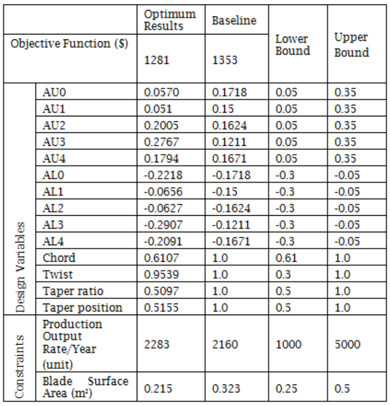
Where, C_M = Material Cost, C_L = Labor Cost, C_E = Equipment Cost

Results and Discussion:

Design optimization is an important engineering design activity. Research on design optimization has considered better solution methods as well as novel formulations. Fig.7 shows the optimization results and Baseline. The objective function reduced 5.3%. The history of convergence is shown in Fig. 8. We could analyze the effect of design parameters without creating the new 3-D CAD models. Based on the optimum design parameters, 3-CAD model has been updated itself under the integrated framework.

Conclusion:

The concept of integrated design is studied using parametric CAD model. It is demonstrated that the cost of an engineering product can be integrated to selected design parameters in CAD and manufacturing process parameters for design optimization. This study aims to provide an effective tool in generating cost driven designs supporting better decision making in the product development process. The methodology proposed here is intended to shorten the lead time in acquiring the cost estimates. The methodology can be used to design more sophisticated parts than the present model. The developed model can be upgraded and integrated other related engineering analysis modules.



		Optimum Results	Baseline	Lower Bound	Upper Bound
Objective Function ($)		1281	1353		
Design Variables	AU0	0.0570	0.1718	0.05	0.35
	AU1	0.051	0.15	0.05	0.35
	AU2	0.2005	0.1624	0.05	0.35
	AU3	0.2767	0.1211	0.05	0.35
	AU4	0.1794	0.1671	0.05	0.35
	AL0	-0.2218	-0.1718	-0.3	-0.05
	AL1	-0.0656	-0.15	-0.3	-0.05
	AL2	-0.0627	-0.1624	-0.3	-0.05
	AL3	-0.2907	-0.1211	-0.3	-0.05
	AL4	-0.2091	-0.1671	-0.3	-0.05
	Chord	0.6107	1.0	0.61	1.0
	Twist	0.9539	1.0	0.3	1.0
	Taper ratio	0.5097	1.0	0.5	1.0
	Taper position	0.5155	1.0	0.5	1.0
Constraints	Production Output Rate/Year (unit)	2283	2160	1000	5000
	Blade Surface Area (m^2)	0.215	0.323	0.25	0.5

Fig. 7: Objective Function, Design variables and Constraints.

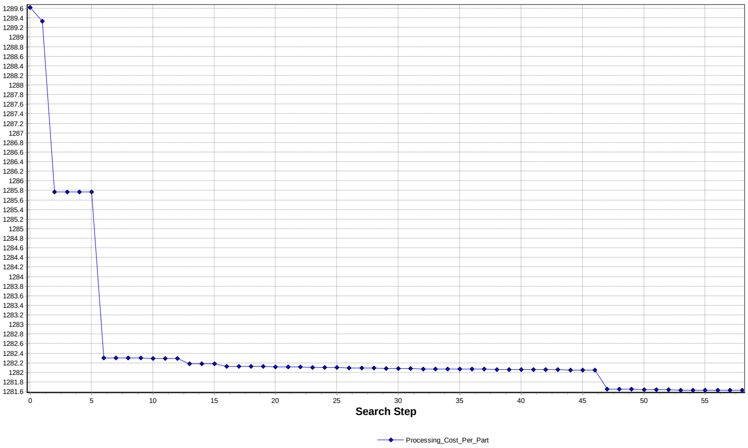


Fig. 8: Convergence graph for the objective function (To minimize the manufacturing cost).

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