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T/BEST: Technology Benefit Estimator Select Features and Applications

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ABSTRACT

A Technology Benefit Estimator (T/BEST) system has been developed to provide a formal method to assess advanced aerospace technologies and quantify the benefit contributions for prioritization. An open-ended, modular approach is used to allow for upgrade and insertion of advanced technology modules. T/BEST's software framework, beginner-to-expert operation, interface architecture, and key analysis modules are discussed. In this paper, selected features and applications of T/BEST are demonstrated. Sample cases pertaining to structural analysis of titanium and composite blades are presented. The performance of hot and cold composite fan blades is also discussed. The cost required to manufacture titanium and composite fan blades is estimated.

INTRODUCTION

Progress in the field of aerospace propulsion promoted the need to assess the benefits gathered by interfacing advanced technologies. These benefits will provide guidelines to identify and prioritize high payoff research areas, help manage research and limited resources, and show the link between advanced and basic concepts. An effort was undertaken at NASA Lewis Research

Center (LeRC) to develop a formal method, T/BEST (Technology Benefit Estimator), to assess advanced aerospace technologies and credibly communicate the benefits of research.

Fibrous composites are ideal for structural applications such as high performance aircraft engine blades where high strength to weight and stiffness to weight ratios are required. These factors along with the flexibility to select the composite lay-up and to favorably orient fiber directions reduce the displacements and stresses caused by large rotational speeds in aircraft engines.

The objective of this paper is to present a computational simulator system that is able to quantify and prioritize the benefits of interfacing advanced technologies. The framework of the T/BEST software, beginner-to-expert operation, the architecture of interfacing various modules, and key analysis modules are described. Examples showing the benefits of utilizing composite to construct fan and compressor blades, and how to update the blade geometry to maximize the rotor's efficiency are presented. Also, a typical blade manufacturing process is summarized.

DESCRIPTION OF T/BEST

Software Framework T/BEST [ref. 1] is a computer software developed at NASA LeRC to successfully communicate and estimate the benefits of introducing new technologies into existing propulsion systems. It has a hierarchical framework that yields varying levels of accuracy of benefits estimation that are dependent on the degree of input details available. This hierarchical feature permits rapid estimation of technology benefits even when the technology is at the conceptual stage. The executive system of T/BEST operates on stand-alone or networked workstations, and uses a UNIX Bourne shell script to control the operation of interfaced modules. Input files for all modules are generated automatically. T/BEST's modular approach allows for modification and addition of analyses modules. All modules in T/BEST inter-communicate via a central data bank named neutral file.

Key engine cycle, structural, stage performance (fluid), mission and cost analyses modules are used in T/BEST to provide a framework for interfacing with advanced technologies. The analyses modules interact with default or user information and component libraries to yield estimates of specific global benefits: range, speed, thrust, capacity, component life, noise, specific fuel consumption, component and engine weights, pre-certification test, mission, performance, engine cost, direct operating cost, life cycle cost, manufacturing cost, and development cost.

The T/BEST executive system is structured to provide the user with user friendly book-keeping facilities. Figure 1 displays the organizational directory tree chart of the T/BEST executive system. All source codes and their executables are stored in pre-specified sub-directories (system's level). The input and output files are deposited under the user's *in* and *out* sub-directories (user's level). The software can be installed for usage by a single user or multi-users on a networked workstation.

Beginner-to-Expert Operation The T/BEST executive system manages the requirements of interfacing disciplines with various levels of complexity. The disciplines interfaced in T/BEST are: thermodynamics, mission, structures, fluid flow, cost, manufacturing, and noise. T/BEST is developed to be used by engineers from various disciplines. Its executive system conforms with three levels of user's expertise as follows:

Beginner A first time user of T/BEST is considered a beginner. Minimum efforts are required to run a study case. The examples library contains several types of engines, supersonic and subsonic, which can be used as initial start-up cases. Also, the executive system allows a beginner to modify only a few default parameters, such as range, fuel and oil costs, etc.. In addition, the on screen display feature directs a beginner on what parameters may be modified.

Intermediate An engineer that has executed T/BEST several times would be considered an intermediate user. At this level, the user can edit and modify the default libraries that include airfoils and materials used in the construction of primary components such as blades and disks.

Expert A user with extensive experience in executing T/BEST should be able to utilize the T/BEST FORTRAN utilities which employ GET and PUT functions for the extraction and addition of data from and to the neutral file respectively. These utilities are very useful and practical when a user decides to add or remove modules to and from T/BEST. The script that manages the execution of T/BEST needs to be updated if a module is being added. The procedure is simple and is done by duplicating a small section in the script and incorporating the names of new modules.

Interface Architecture Each analysis module in T/BEST is executed independently of the others. Most analysis modules utilize pre-and-post processors to automatically generate the required input files and filter output files respectively. A pre-processor picks-up information from the neutral file and could use default libraries to generate input files for a specific module. The neutral file, a central data bank system, is used as a network to exchange information among all modules. Each parameter in the neutral file is defined by a unique keyword accompanied by its corresponding numerical value. The post-processor filters the output file of a module and updates the neutral file to include relevant responses which are used subsequently to generate input files for other modules.

KEY ANALYSIS MODULES

The T/BEST executive system contains, by default, independent modules used to conduct a wide array of analyses. Only the modules that hold key and major analytical capabilities are described in this paper. Figure 2 depicts the default key computational simulation modules of the T/BEST executive system. For example, the miscellaneous capabilities block shown in

Figure 2 represents minor modules that are dedicated to estimate engine mean time between repair, number of city pairs that can be reached based on a given range, life cycle maintenance, manufacturing cost, and noise level.

Engine Cycle & Weight Analyses (NNEPWATE) This module combines two in-house NASA LeRC computer codes: NNEP89 [ref. 2] and WATE89 [ref. 3]. The NNEP89 code conducts a one dimensional steady state thermodynamics analysis of turbine engine cycles. It provides the T/BEST neutral file, through its post-processor, with thrust, specific fuel consumption, and fuel flow and flow rates at various altitudes and speeds. The WATE89 code estimates an initial engine weight and major envelop dimensions of large axial flow aircraft engines. It determines the weight of each major component in the engine, such as compressors, burners, and turbines. Stage and component weights, pressures and temperatures, and key blade description parameters (length of blade and aspect ratio, etc...) are obtained from the WATE89 output.

Flight Optimization System (FLOPS) The Flight Optimization module [ref. 4], developed at NASA Langley Research Center, is responsible for conducting mission and cost analyses. The FLOPS mission performance capability uses the calculated weights, aerodynamics, and the NNEPWATE propulsion system data to calculate performance. Optimum climb, cruise, and descent profiles are predicted by this module. The cost analysis obtained from FLOPS includes detailed airframe costs, engine development and production costs, direct and indirect operating costs, and return on investments.

Blade Structural Analysis (BLASIM) This module [ref. 5] was developed at NASA LeRC to assess the damage caused by ice impact on engine blades. BLASIM is a blade structural analyzer module capable of assessing local and root ice impact damage, local and root Foreign Object Damage (FOD). Also, BLASIM performs static, dynamic, resonance margin, flutter, and fatigue analyses of engine blades. This module can handle the following blade types: solid, hollow, superhybrid, and composite. For composite blades, BLASIM utilizes ICAN [ref. 6]

(Integrated Composite Analyzer) to generate material properties. The ICAN code was primarily designed to analyze the hygro-thermomechanical response/properties of fiber reinforced/resin matrix type layered composites.

In T/BEST, an airfoil library containing several NACA (National Advisory Committee on Aeronautics) airfoils has been built-in to allow a beginner user to automatically construct the blade. This library allows for addition and removal of airfoils and for the definition of blade material type. The material properties are obtained from a dedicated data bank that contains properties for a large number of fibers and matrices. Prior to executing T/BEST, the user has the option of specifying the blade profile which is defined in the airfoil library for each stage of each rotating component in the engine.

The BLASIM input files are generated automatically for each stage based on geometric parameters obtained from NNEPWATE, such as aspect ratio, blade length, and hub-to-tip ratio. All input and output files are identified easily because of a unique naming convention. For example, BFAN0201.INP and BFAN0201.OUT are the BLASIM input and output files of the first stage of the second engine component (FAN). Once the structural analysis conducted by BLASIM is completed, response parameters such maximum tip displacements, response from impact damage (if applicable), blade weight, frequencies and root stress are updated in the neutral file. The blade geometry is subsequently updated by T/BEST to include deformations caused by the combined mechanical loading: pressure and centrifugal. In this paper, the structural benefits obtained by using composite over titanium to construct fan and compressor blades are identified .

Transonic Flow Analysis (MTSB) The MTSB module [ref. 7] is a NASA LeRC computer code designed to obtain a detailed subsonic or transonic flow solution on the hub-shroud mid channel stream surface of a single blade row. For subsonic flow, the analysis is based on the stream function and consist of the solution of simultaneous, nonlinear, finite difference equations. For locally supersonic flow, the solution is obtained by a combination of a finite difference, stream function and velocity gradient solutions. The MTSB module supplies the T/BEST neutral file at each stage with the overall rotor's efficiency and detailed efficiency losses comprised of: profile, endwall, section loss, clearance, incidence, and windage. An example showing the effect of the blade position on the stage performance is discussed in the next section.

Manufacturing (MNFTR) The manufacturing module, developed at NASA LeRC, yields the required stock material weight and component cost using a Maurer cost and weight estimation method [ref. 8]. The neutral file supplies the manufacturing module with the process type (defaulted to Maurer) and the weight for each component in the engine cycle analysis. The Maurer cost formulation is calculated by first determining the relative weighting factor which is equal to the product of the relative material cost and the relative machining cost. Then the Maurer factor is computed by taking the product of the weighting factor and the weight of stock material needed to manufacture a component. The range of the Maurer factor constitutes the type of correlation needs to be used to formulate the cost function. Other processes are contained in a pre-assigned process file that can be used to extract component cost as a function of the manufacturing processes being used to make the component. A sample example demonstrating the manufacturing capability is presented in the next section.

BENEFITS OF INTRODUCING COMPOSITE BLADES

A comparative study was carried out to show the benefits of constructing fan, and compressor blades of a supersonic engine with titanium and graphite epoxy [+45,-45,90,0]s. The fan and the high pressure compressor (HPC) consisted of two and five stages respectively. The blade was constructed with NACA 64-206 airfoil [ref. 9]. For each stage, as obtained from NNEPWATE, the T/BEST neutral file provided the geometric parameters required to define the blade, such as blade taper ratio, aspect ratio, hub and tip radii, and blade root angle. The first stage fan blade airfoil, load, and geometric description are shown in Figure 3. The same loading conditions were applied to both blades, graphite epoxy and titanium. Loads applied included combined centrifugal and pressure.

Structural Benefits The structural analysis of titanium and graphite epoxy blades is carried out by the BLASIM module. The results shown in Figures 4 through 9 are intended to illustrate the benefits obtained from the usage of graphite epoxy in the construction of the blade. These benefits include enormous reduction in displacements and stresses as well as weights of the blades.

Figure 4 shows a comparison of the titanium and graphite epoxy blades tip displacements for the fan and the high pressure compressor. The results indicate that the tip displacements for the graphite epoxy blade are much lower (over 50%) than the ones obtained for the titanium blade. Figures 5 and 6 show the uncamber and untwist of the titanium and graphite epoxy blades. The graphite epoxy blade uncamber and untwist are slightly larger than the ones of the titanium blade. A comparison of the stress at the root of the graphite epoxy and the titanium blades is shown in Figure 7. The stress at the root of the graphite epoxy blade is lower (about 25%) than the one obtained for the titanium blade. Figure 8 displays a comparison of the first mode natural frequency of the titanium and graphite epoxy blades. The composite blades are stiffer and have higher natural frequencies (about 8%). Figure 9 shows that the graphite epoxy blade is much lighter than the titanium blade.

Performance Benefits The fluid flow analysis is carried out by the MTSB module. It utilizes the same blade profile defined for structural analysis. The neutral file contains data, such as flow rate, pressure, and temperature at each stage, required for the flow analysis. The example presented here pertains to the first stage of the fan. The flow analysis is conducted at two blade positions: cold (undeformed) and hot (deformed). The hot position of the blade was derived by updating the blade geometry to reflect deformations caused by centrifugal and pressure loadings. The results obtained are presented in Figure 10. The blade's overall efficiency at hot position was 89.44% compared to 88.46% at the cold position. Losses due to incidence are larger at the blade's cold position than those at the hot position. The hot position of the blade must be accounted for at the design stage to prevent losses in efficiency.

Manufacturing Benefits The Maurer normalized stock weight and cost needed to manufacture titanium and graphite epoxy blades are shown in Figure 11. The results indicate that the material stock weight used to make one graphite epoxy blade (1st stage of fan) is about 47% less than the one required to make a titanium blade. Also, the cost required to manufacture the composite blade was about 57% less than the one of the titanium blade. When manufacturing metal blades, a portion of the material stock weight is wasted during the machining sub-process. Also, the forging sub-process adds to the price of manufacturing metal blades because of energy and labor costs.

A sample cost pie chart of a manufacturing process of resin matrix composite blades is shown in Figure 12. The process is made of 11 sub-processes. The cost absorbed in each sub-process is shown in the pie chart. The chart indicates that the largest cost (57.1%) involved the first sub-process (procure material, cut and collate plies). The lowest cost (about 0.8%) is associated with the sub-process required to machine the tip. These sub-processes are industry standards and can be modified by the user. Note that these sub-processes do not correspond to the graphite epoxy blade that is discussed earlier but are used in this paper to illustrate a typical manufacturing process.

CONCLUSIONS

The capabilities of T/BEST in estimating the benefits of interfacing advanced technologies were successfully demonstrated. T/BEST is a unique software because of its modular structure, user friendliness, portability, and its distinct ability to be operated by users with various levels of expertise. Through the sample cases presented, the T/BEST executive system identified the structural benefits obtained by using composite material to construct fan and compressor blades.

When manufacturing fan blades, the usage of composite material offers great advantages due to significant reduction in weight and cost. To achieve maximum performance, the blade should be designed in hot position.. The Technology Benefit Estimator software can be used by designers and engineers of various disciplines to assess the benefits gathered by interfacing advanced technologies.

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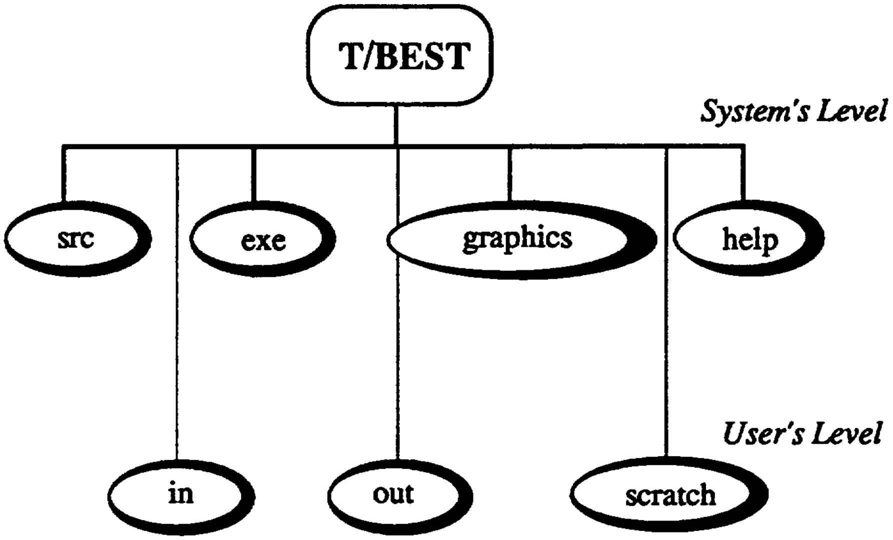


Figure 1. Organizational directory tree chart of the T/BEST Executive System

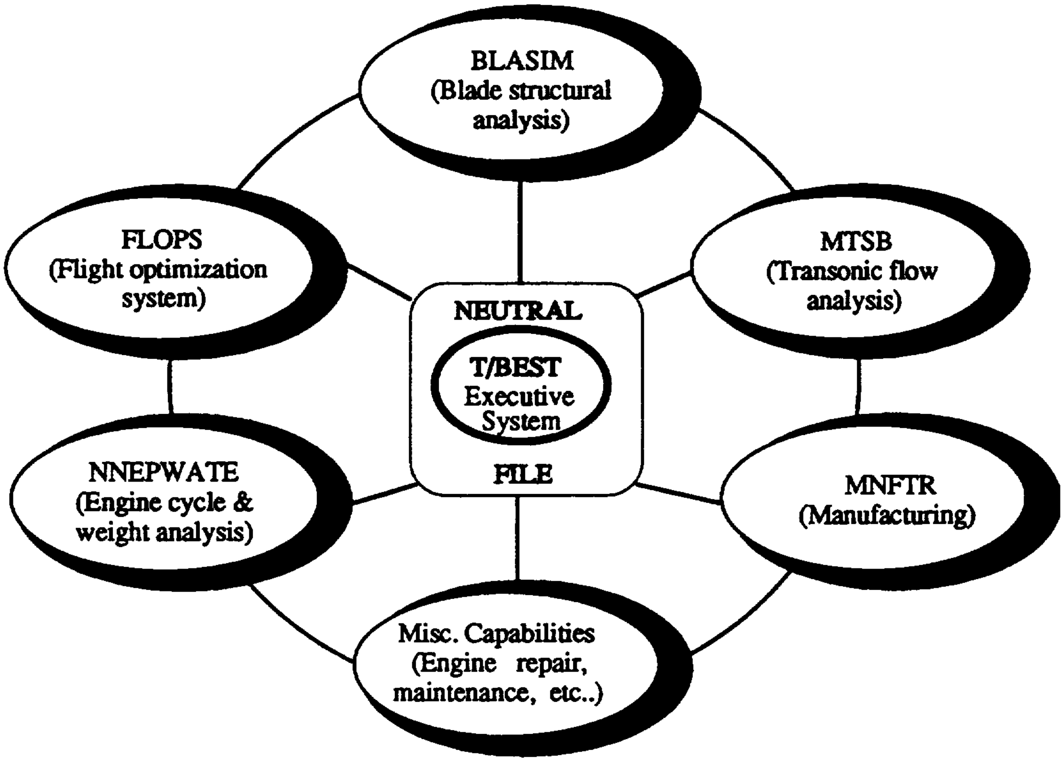
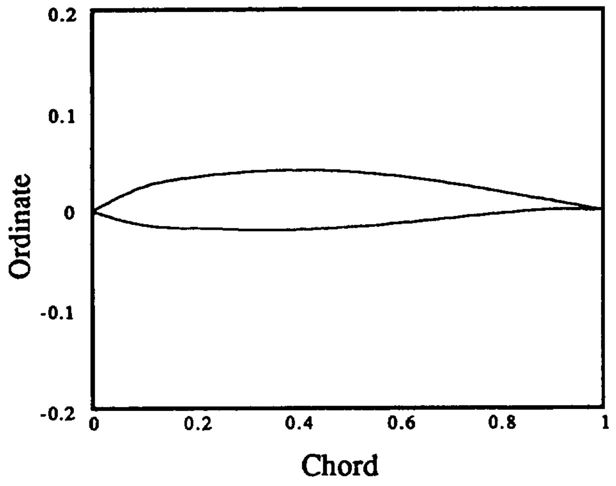


Figure 2. Default computational simulation modules of the T/BEST Executive System



a) NACA 64-206 airfoil

Engine Component: FAN,	*Stage: 1*
Operating RPM	6106
Hub Radius	11.77 in
Tip Radius	30.97 in
Number of Blades	33
Aspect Ratio	3.0
Blade Root Angle	18.45°
Stagger Angle	35.0°

b) Fan blade load and geometry description

Figure 3. Fan blade airfoil, load, and geometry description

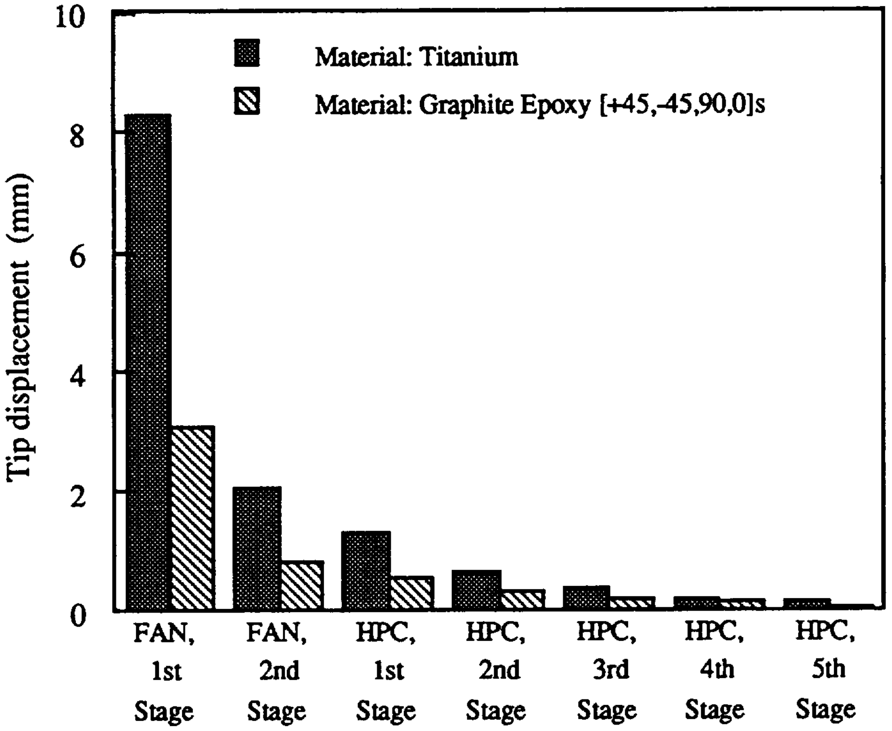


Figure 4. Maximum spanwise tip displacement - NACA 64-206 blade - Structural response

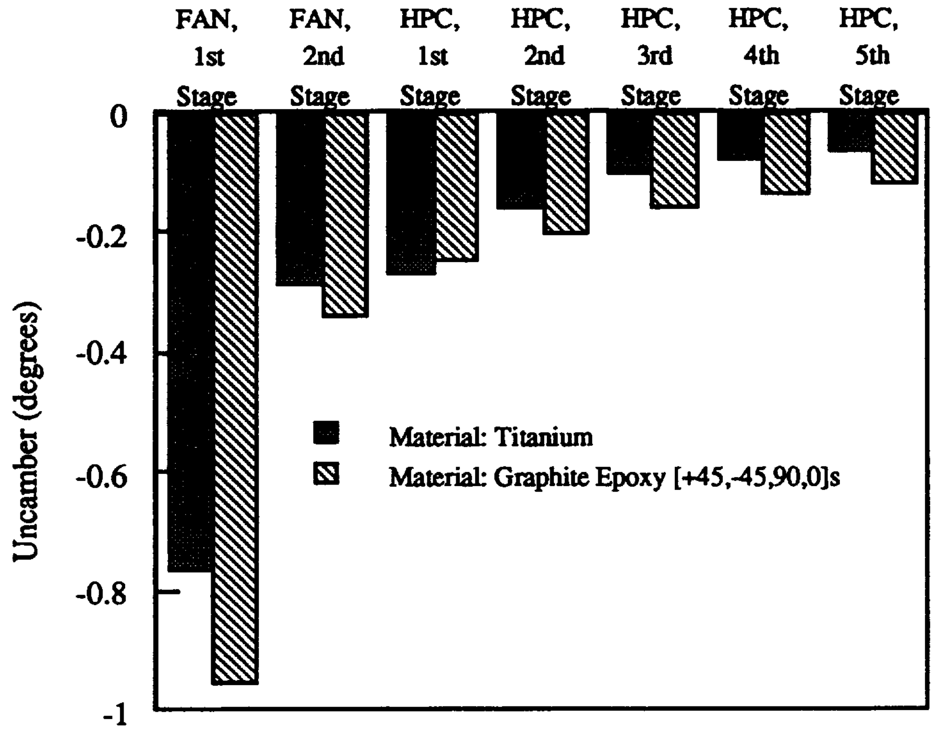


Figure 5. Uncamber- NACA 64-206 blade - Structural response

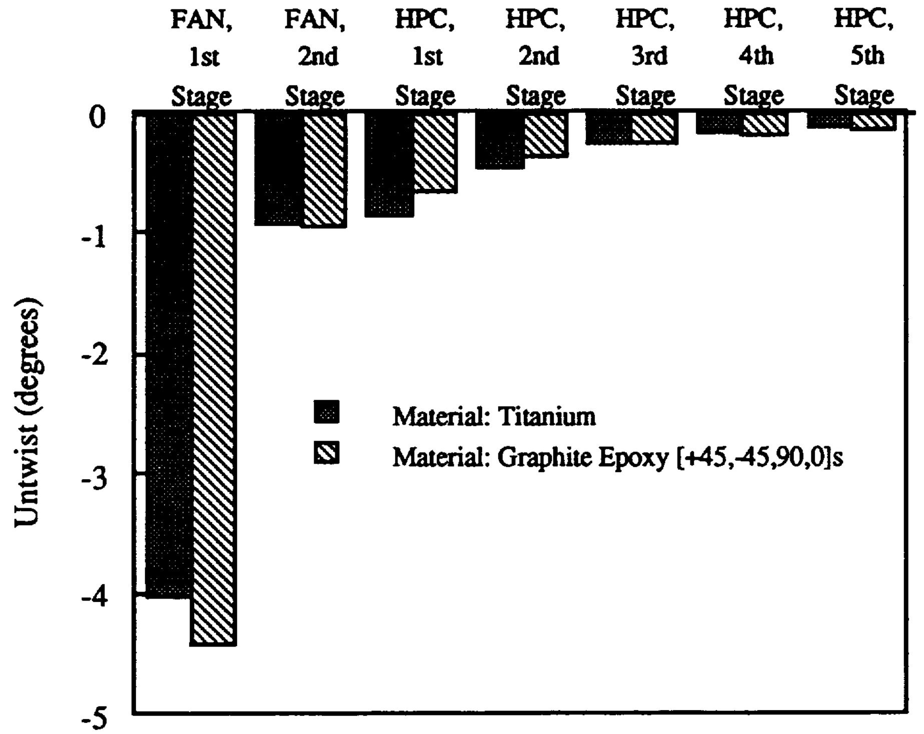


Figure 6 Untwist - NACA 64-206 blade - Structural response

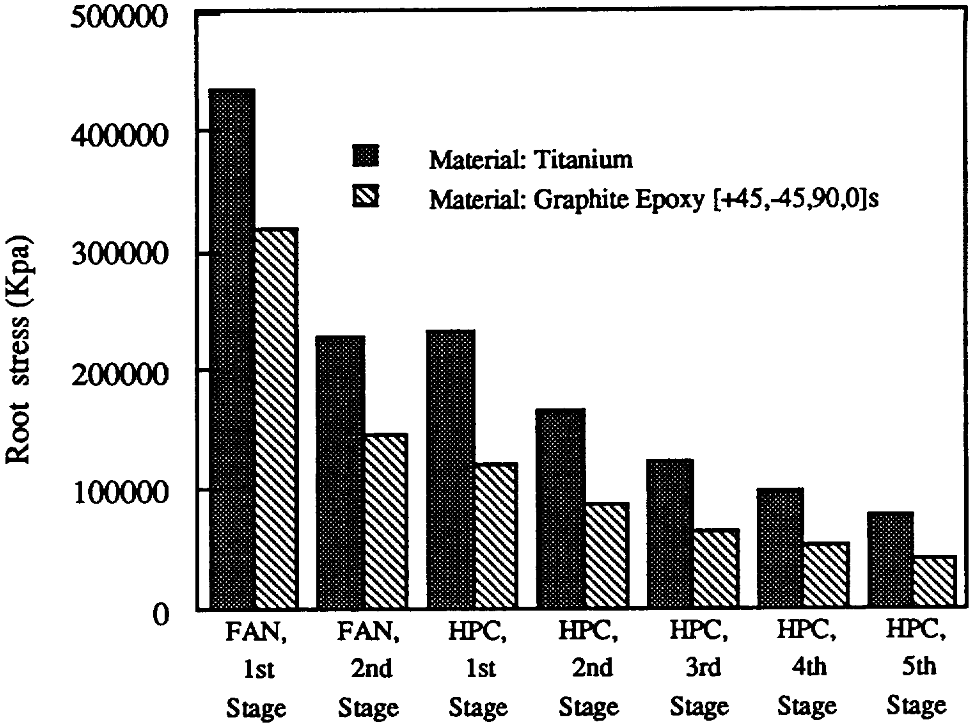


Figure 7. Root stress- NACA 64-206 blade - Structural response

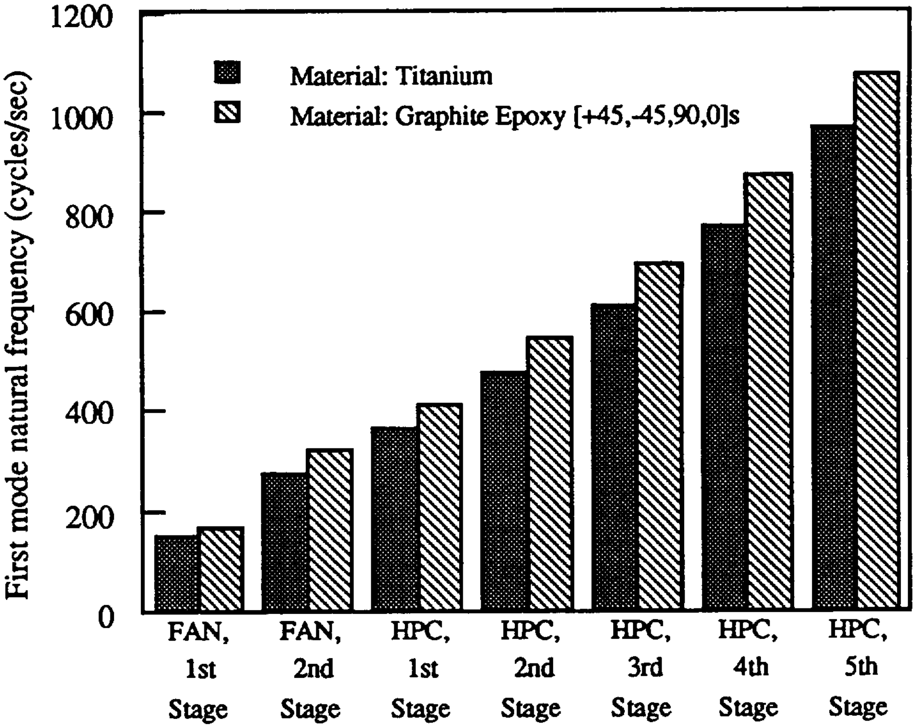


Figure 8. First mode natural frequency - NACA 64-206 blade - Structural response

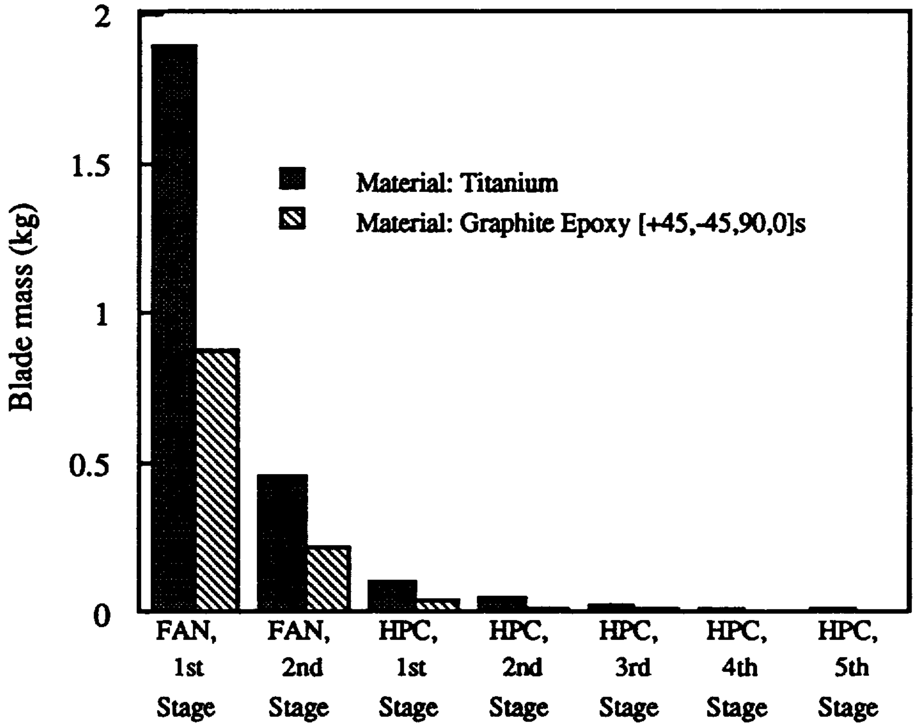


Figure 9. Solid and composite blade mass - NACA 64-206 blade

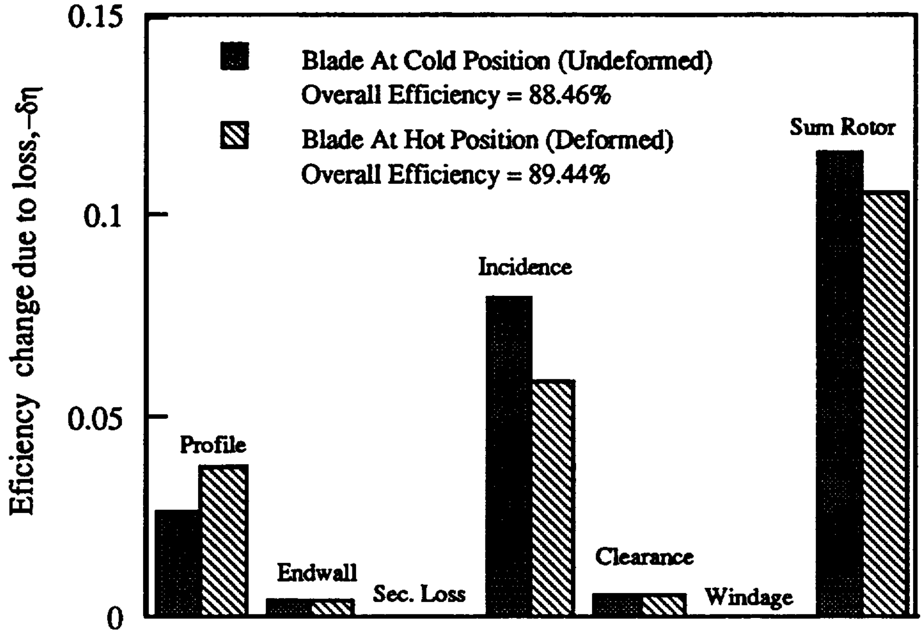


Figure 10. Fan- first stage efficiency changes due to loss for cold and hot blade positions. Graphite Epoxy [+45,-45,90,0]s, NACA 64-206 blade

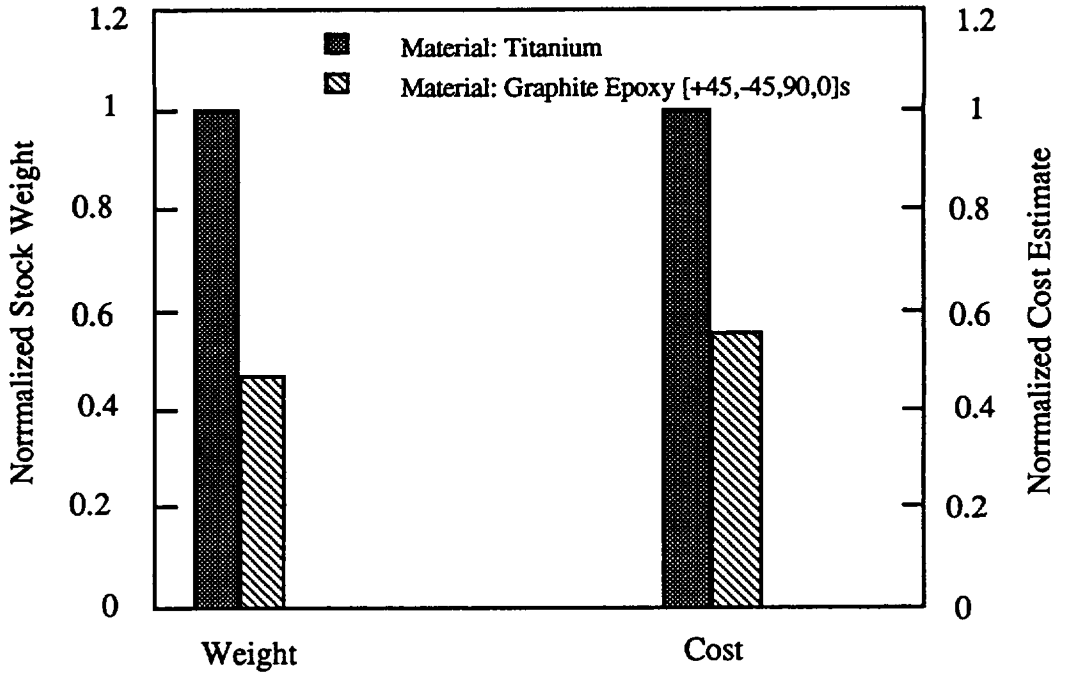


Figure 11. Maurer stock weight and cost estimation for manufacturing a fan blade.

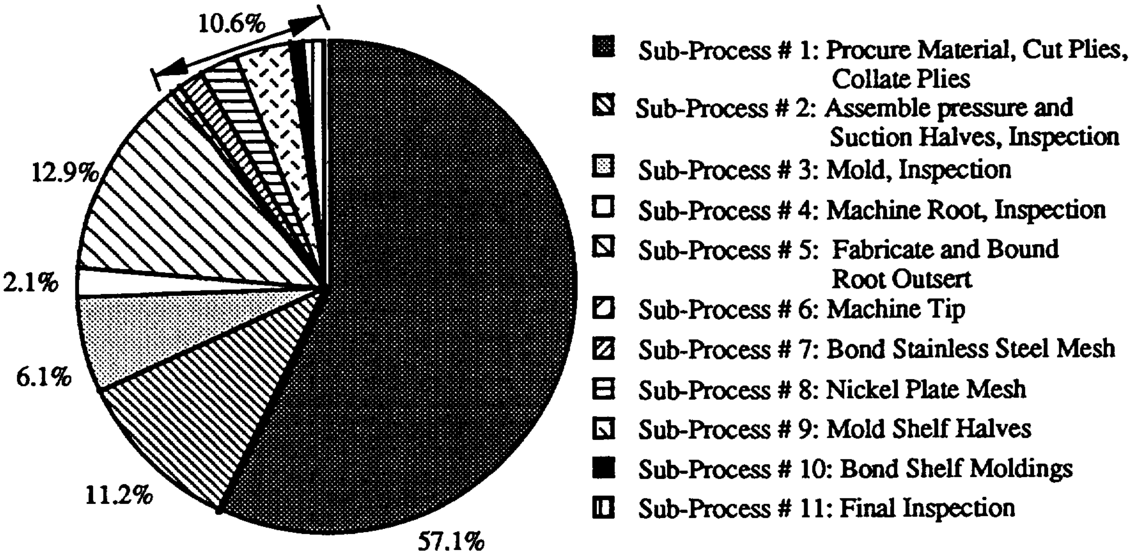


Figure 12. Cost pie chart of a manufacturing process of resin matrix composite blades

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13. ABSTRACT ***(Maximum 200 words)***

A Technology Benefit Estimator (T/BEST) system has been developed to provide a formal method to assess advanced aerospace technologies and quantify the benefit contributions for prioritization. An open-ended, modular approach is used to allow for upgrade and insertion of advanced technology modules. T/BEST's software framework, beginner-to-expert operation, interface architecture, and key analysis modules are discussed. In this paper, selected features and applications of T/BEST are demonstrated. Sample cases pertaining to structural analysis of titanium and composite blades are presented. The performance of hot and cold composite fan blades is also discussed. The cost required to manufacture titanium and composite fan blades is estimated.

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