JOURNAL OF AIRCRAFT
Vol. 36, No. 1, January–February 1999

Coupled Multidisciplinary Optimization of Engine Structural Performance

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Effective computational simulation procedures are described for modeling the inherent multidisciplinary interactions that govern the accurate response of propulsion structural systems. Results are presented for propulsion system structural responses including multidisciplinary coupling effects using 1) coupled multidiscipline thermal/structural/acoustic tailoring, 2) an integrated system of multidisciplinary simulators, 3) coupled material-behavior/fabrication process tailoring, 4) sensitivities using a probabilistic simulator, 5) a coupled materials/structures/fracture/probabilistic behavior simulator, and 6) engine structure technology benefit estimators. The results demonstrate that superior designs can be achieved if the analysis/tailoring methods account for the multidisciplinary coupling effects.

Introduction

ENGINE structural systems are inherently multidisciplinary, i.e., the true system response is the coupled effect of all the participating disciplines and the aggregate of the responses and interactions of the system components (Fig. 1). Present analyses tend to focus on a single-discipline response within a local region, e.g., a single component (Fig. 2). Suitable approximations are then used to extend these analyses to subsystems and systems (Fig. 3).

The performance and reliability of propulsion structural systems depend on the interaction of their subsystems, which, in turn, depend on the interaction of their respective components.[1] The performance of a specific component depends on the coupled effects for the system multidisciplinary interaction on the component response (Fig. 1). Further, the integrated system response depends on the progressive and interacting influence of the coupled service loads/environments at all levels from subcomponent, to component, to subsystem, to system (Fig. 3). Interaction phenomena of interest include flutter, rotor instability, fatigue, flow separation, nonuniform combustion, blade containment, and noise suppression. The determination of aerothermodynamic system performance has traditionally relied on prototype tests, whereas structural reliability has been determined from field data.

The analysis of propulsion structural systems/components involves a combination of disciplines including fluid mechanics, thermal sciences, structural mechanics including weight, material sciences, acoustics, electromagnetic, and control theory. In addition, it includes fabrication performance and cost so that structural performance can be traded (optimized) against cost and fabrication simplicity. The following summarizes how the coupled multidisciplinary simulation may be represented in an array form:

$$\begin{Bmatrix} \{A\} \\ \{T\} \\ \{S\} \\ \{M\} \\ \{F\} \\ \{P\} \\ \{C\} \end{Bmatrix} = \begin{bmatrix} [A_A^A] & [T_A^T] & [S_A^S] & [M_A^M] & [F_A^F] & [P_A^P] & [C_A^C] \\ [A_T^A] & [T_T^T] & [S_T^S] & [M_T^M] & [F_T^F] & [P_T^P] & [C_T^C] \\ [A_S^A] & [T_S^T] & [S_S^S] & [M_S^M] & [F_S^F] & [P_S^P] & [C_S^C] \\ [A_N^A] & [T_N^T] & [S_N^S] & [M_N^M] & [F_N^F] & [P_N^P] & [C_N^C] \\ [A_F^A] & [T_F^T] & [S_F^S] & [M_F^M] & [F_F^F] & [P_F^P] & [C_F^C] \\ [A_P^A] & [T_P^T] & [S_P^S] & [M_P^M] & [F_P^F] & [P_P^P] & [C_P^C] \\ [A_C^A] & [T_C^T] & [S_C^S] & [M_C^M] & [F_C^F] & [P_C^P] & [C_C^C] \end{bmatrix} \begin{Bmatrix} \{A\} \\ \{T\} \\ \{S\} \\ \{M\} \\ \{F\} \\ \{P\} \\ \{C\} \end{Bmatrix}$$

The degree of resolution within a specific discipline is determined by the magnitude of local effects and the extent of their region of influence. Engine structure simulation method development has been an ongoing research activity at NASA Lewis Research Center for the past two decades. An open-ended integrated approach to engine structure simulation, summarizing developments and results up to 1981, are described in Ref. 1. The progression of the obtained methods to computational engine structures analysis and results are described in Ref. 2. The continuing progression of the genesis of numerical propulsion simulation systems is described in Ref. 3. The parallel development of structure technology benefit estimators is described in Ref. 4. During the course of those developments it became evident that the next step in the progression is quantification of the component interaction effects. To credibly quantify local effects, coupled multidisciplinary methods are required. Therefore, the objective of this paper is to present results demonstrating the multidisciplinary interaction in propulsion structural systems using formal coupled multidisciplinary methods. It is important to note that this paper focuses on the importance of discipline simulators and not on optimization algorithms. Appropriate references are cited for detailed descriptions of methods and attendant computer codes. Though the present review is limited to NASA Lewis Research Center's developments, it reflects, in a broader context, the state of the art. Industry, academia, and other research institutes participated in the developments, as is evident from the select references cited.

Multidisciplinary Coupling Representation

Recent advances in the computational simulation of fluid, thermal, structural, material, acoustic, electromagnetic response, and computational automatic controls, provide an opportunity to consider the development of coupled multidisciplinary computational simulation methods. The coupling methods provide the formalism to generate the terms shown in the array shown earlier. Single discipline simulations produce the diagonal subarrays, whereas coupled multidisciplines produce the off-diagonal terms. Many computational methods/codes

Received July 12, 1998; revision received July 14, 1998; accepted for publication Aug. 9, 1998.

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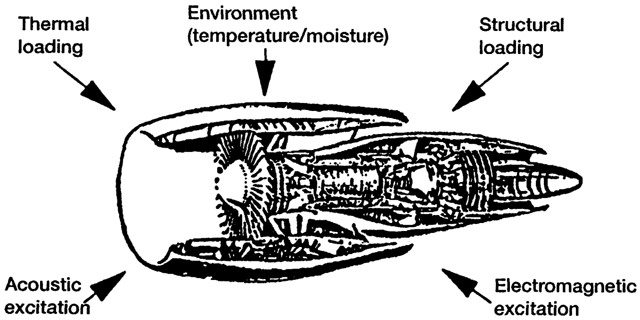


Fig. 1 Engine components under service-environment loadings.

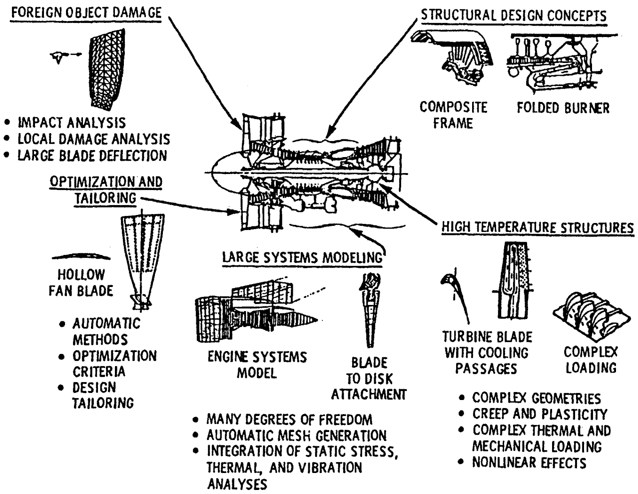


Fig. 2 Engine structural components amenable to computational simulation.

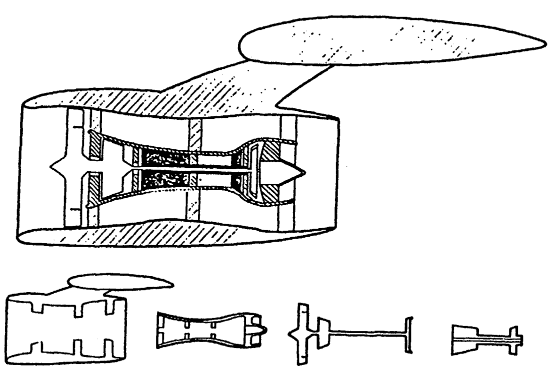
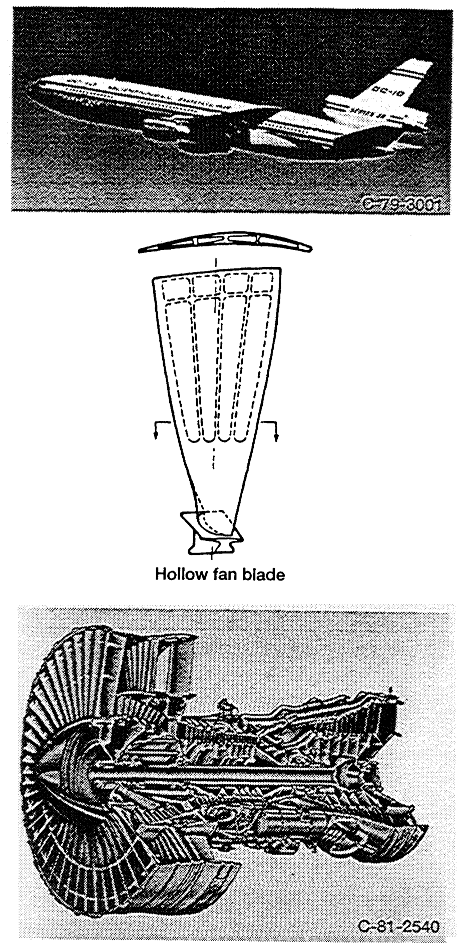


Fig. 3 Engine structure/substructure/component.

are available for solving unidisciplinary problems, as mentioned previously. In this section, we describe how existing computational methods/codes are used to simulate the multidisciplinary coupled response of various propulsion components, which are subjected to a multitude of simultaneous loads.

Multidisciplinary Engine Blade Optimization

A substantial effort has been devoted to multidisciplinary blade optimization. Four different computer codes were developed for that purpose. Structural tailoring of engine blades is designed to tailor blade designs to satisfy all mechanical design requirements while minimizing weight and optimizing other performance variables.[5,6] Typical results from the computer code are shown in Fig. 4. Suitable modifications for application to Space Shuttle main engine blades to accommodate extreme thermal conditions are described in Ref. 7. This computer code progressed to tailoring of swept propfans,[8] typical results are shown in Fig. 5.



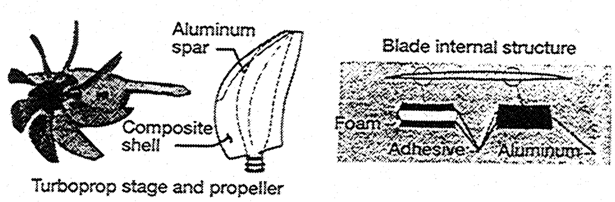
Current design procedures:

• Weight	17 lb
• ROI	3.0 percent
• Prof. effort;	52 weeks

STABL derived design

• Weight	16 lb
• ROI	3.3 percent
• Prof. effort;	1 weeks

Fig. 4 Structural tailoring of engine blades (STAEBL).



MULTI-DISCIPLINARY ANALYSIS MODULES

- ADS OPTIMIZER
- BLADE MODEL GENERATION
- AERODYNAMIC ANALYSIS
- ACOUSTIC ANALYSIS
- STRESS AND VIBRATIONS ANALYSIS
- FLUTTER ANALYSIS
- 1 P FORCED REPONSE

TYPICAL ANALYSIS RESULTS

	INITIAL	FINAL
EFFICIENCY, PERCENT	82.86	83.17
NEAR FIELD NOISE, DB	143.8	137.3
WEIGHT, LB	41.1	41.2
DOC	−.853	−4.201

Fig. 5 Structural tailoring of turboprop blades.

The fourth computer code in that sequence evolved for the need to evaluate blade designs specifically for ice impact.[9] An innovative progressive substructuring technique to efficiently evaluate the local impact damage was employed. A schematic depicting the physics simulated is shown in Fig. 6. The progressive finite element substructuring concept employed is shown in Fig. 7. Typical results obtained are listed in Table 1. Collectively, the results show that substantial improvements in engine structural performance are obtained by using multidisciplinary coupling: 1) 98% reduction in design effort, 2) 10 dB reduction in near-field noise, and 3) 20% reduction in weight for ice-impact resistant blades.

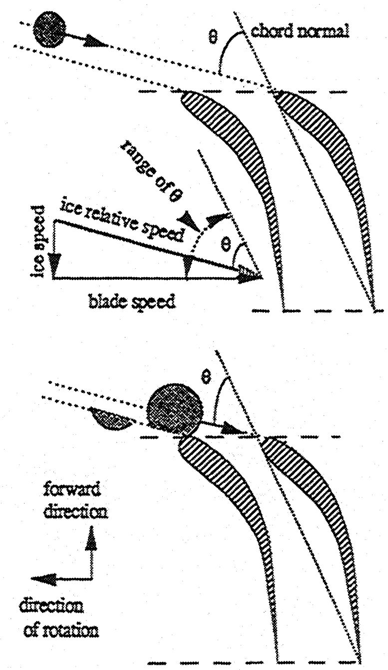


Fig. 6 Geometry of ice impact on an engine blade.

Coupled Multidiscipline Tailoring

A more recent development is a coupled multidisciplinary composite-materials/hygral/thermal/structural/acoustic/electromagenetic/composite tailoring code, CSTEM,[10] which can be used to tailor the single or multidiscipline response of propulsion structures. CSTEM was used for tailoring a multi-layered-composite fan blade subjected to multidiscipline conditions (Fig. 8, Ref. 11). The composite materials' behavior was analyzed using an integrated composite analyzer,[12] starting from the lowest composite scale (fiber/matrix constituents) to higher scales (ply, laminate), using composite micromechanics and laminate theory (Fig. 9). The laminate's material behavior

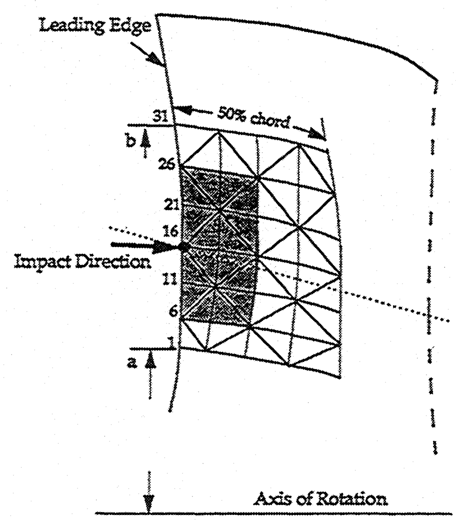
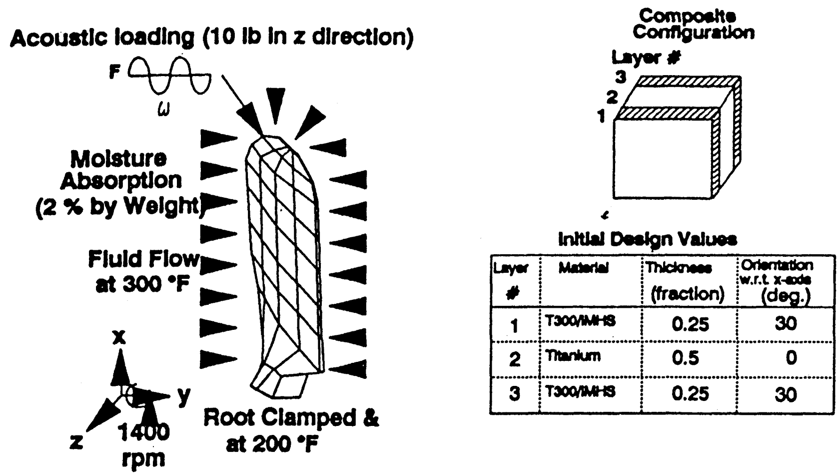


Fig. 7 Finite element model for local impact analysis.

Table 1 Summary of optimization results, effect of impact region[a]

Design parameter	Lower bound	Upper bound	Initial design	Optimum designs, ice impact region, %		
				25–65	40–80	50–90
Root chord length, in.	0.900	1.200	1.02307	0.9000[b]	0.90000[b]	0.9000[b]
Thickness at station 2, in.	0.600	2.000	0.89270	0.84094	0.66181	0.78194
Thickness at station 5, in.	0.080	0.200	0.14470	0.15942	0.14984	0.13408
Thickness at station 7, in.	0.015	0.200	0.08370	0.09126	0.11470	0.08352
Thickness at station 9, in.	0.015	0.200	0.05760	0.04266	0.04997	0.05768
Thickness at station 11, in.	0.015	0.200	0.03360	0.02555	0.02974	0.034415
Ply angle, deg	−90.0	+90.0	45.0000	42.58	45.2807	45.31
Blade weight, lbf	——	——	0.79126	0.70252 (−11.31%)	0.62524 (−21.07%)	0.64054 (−19.14%)
Leading-edge strain, %						
Initial	——	3.0	——	0.1077	0.7110	2.608
Final	——	——	——	0.066	0.411	2.637
Root static stress, psi						
Initial	——	4000	——	1936.78	1931.04	1901.04
Final	——	——	——	1987.44	2381.96	1876.36
Maximum root damage function						
Initial	——	1.0	——	0.6522	3.5231[c]	3.9221[c]
Final	——	——	——	0.0061	0.4169	0.6699
Natural frequency f_1, cps						
Initial	150	——	——	160.11	170.94	160.42
Final	——	——	——	181.29	169.19	150.91[d]
Natural frequency f_2, cps						
Initial	500	——	——	494.13[c]	528.22	575.70
Final	——	——	——	500.28[d]	514.53	566.14
Natural frequency f_3, cps						
Initial	800	——	——	742.34[c]	686.67[c]	812.47
Final	——	——	——	838.98	797.42[d]	799.97[d]
Resonance margin mode-1-2E, %						
Initial	5.0	——	——	25.66	33.10	25.68
Final	——	——	——	40.92	31.29	18.68
Number of function evaluations	——	——	——	105	78	77

[a]Revolutions per minute = 3600; ice size = 0.8 in.; ice speed = 150 kn. [b]Active side constraint. [c]Initially violated constraint. [d]Active constraint.



Layer #	Material	Thickness (fraction)	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	0.25	30
2	Titanium	0.5	0
3	T300/IMHS	0.25	30

Fig. 8 Multimaterial multilayered composite fan blade: initial design under multidisciplinary loadings.

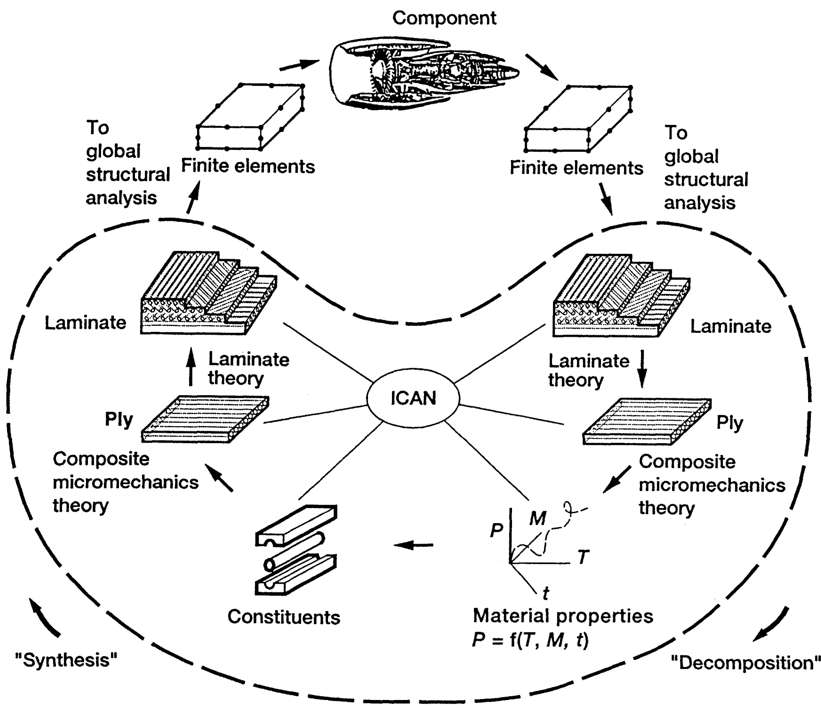
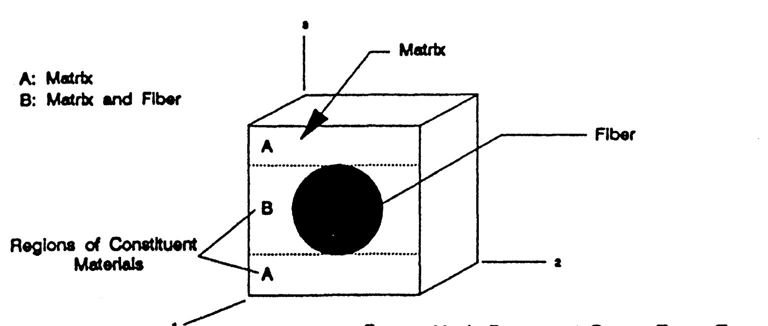


Fig. 9 Integrated composite analysis (ICAN).



$$\frac{P_M}{P_{Mo}} = \left[\frac{T_{GW} - T}{T_{GD} - T_o}\right]^{1/2}$$

$$T_{GW} = (0.005\,M^2 - 0.1\,M + 1)\;T_{GD}$$

P_M = Matrix Property at Current Temp., T

P_{Mo} = Matrix Property at Reference Temp., T_o

T_{GW} = Wet Glass Transition Temp.

T_{GD} = Dry Glass Transition Temp.

M = Moisture % by Weight

Fig. 10 Regions of constituent materials and nonlinear material characterization model.

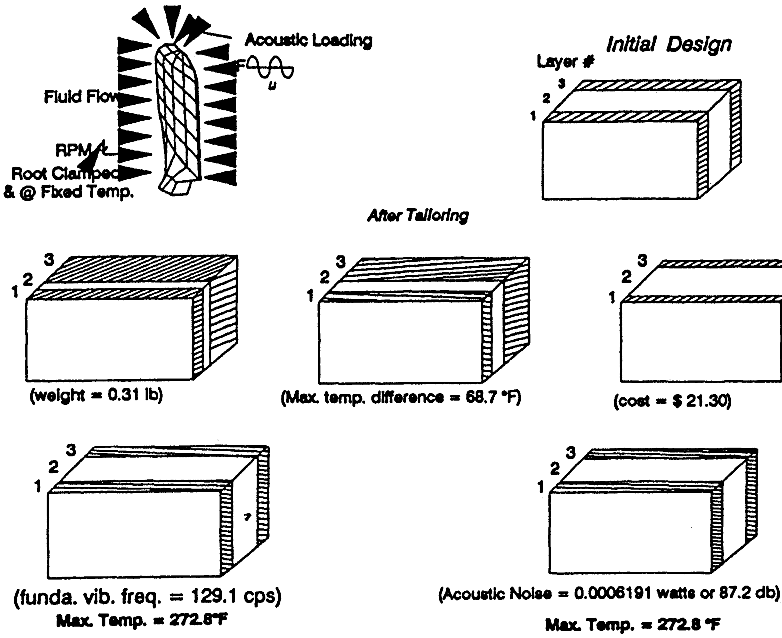


Fig. 11 Multimaterial multilayered composite fan blade: tailored design under multidisciplinary loadings.

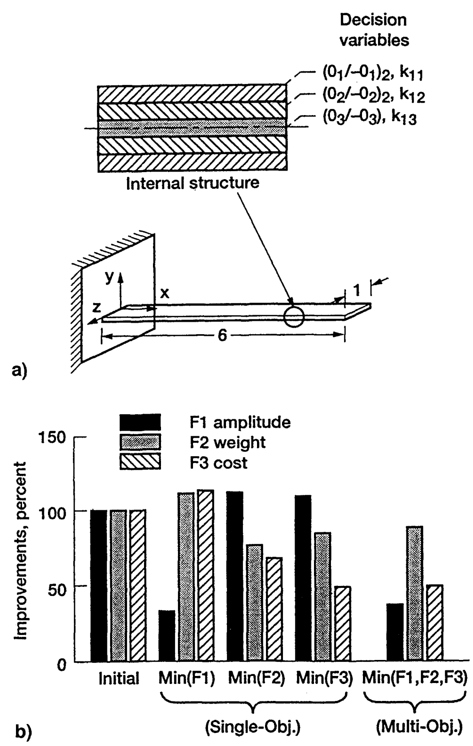


Fig. 12 Multiobjective optimization: a) candidate composite structure, graphite/epoxy (0.50 fiber volume ratio, 70°F) and b) initial and optimum objective values.

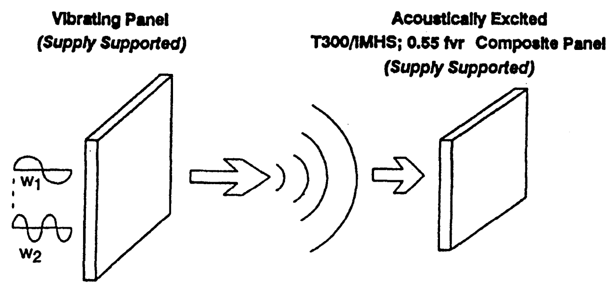


Fig. 13 Acoustically excited composite panel.

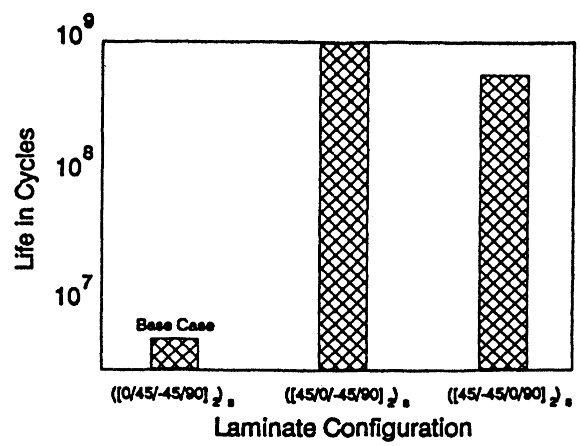


Fig. 14 Coupled composite-material/hygral/thermal/structural/acoustic simulation: effect of laminate configuration.

was used to determine global structural response using finite element methods. The global structural response was then decomposed to the lower composite scales using laminate theory and composite micromechanics. A nonlinear material characterization model (Fig. 10) was used at the constituents scale to account for the effects of service environments.

The laminate configurations of the initial and tailored fan blade designs are shown in Fig. 11. The middle part of Fig. 11 shows three cases of tailored laminate configurations as a result of unidisciplinary tailoring for weight, maximum temperature difference, and cost, separately. The cases, shown at the bottom of Fig. 11, are for the coupled multidisciplines, namely, coupled composite-mechanics/heat transfer/vibrations/acoustic responses. The effect of heat transfer loads was carried through the temperature profiles at all composite scales that, in turn, affect the materials' behavior and, thus, the vibration response of the blade. The latter case includes the effects of temperature on the blade's acoustic characteristics. The acoustic response includes all of the interaction effects, namely, 1) heat transfer loads; 2) thermal, mechanical, and acoustic resistance of the material; and 3) blade vibration characteristics. CSTEM provides a wealth of information such as the laminate configurations required for tailored responses of

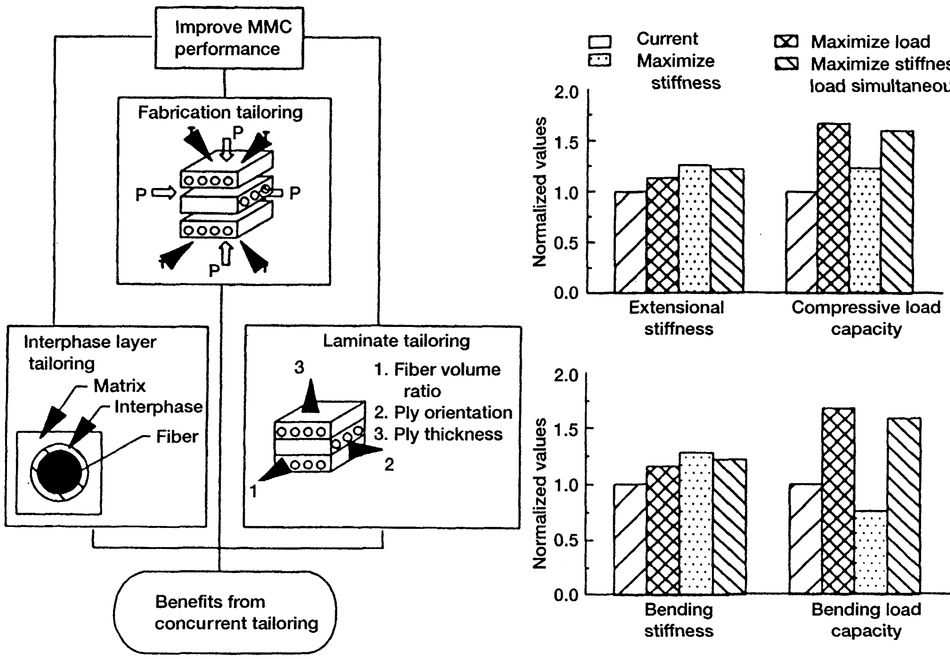


Fig. 15 Metal matrix laminate tailoring to improve load-carrying capacity.

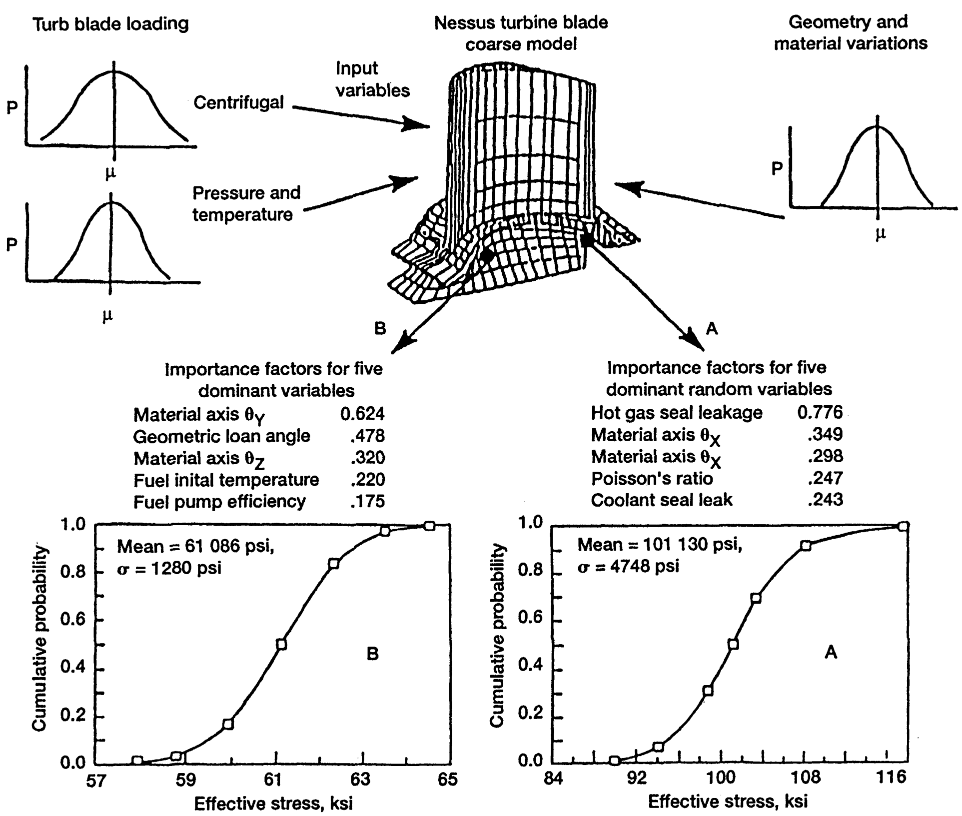


Fig. 16 Probabilistic component stress and sensitivity analyses.

different disciplines, which can sometimes be opposite to each other, as is evident from Fig. 11. The off-diagonal terms, shown earlier in the text, can be developed by evaluating the other disciplines at the optimum design. The important point to note is that coupled multidisciplinary simulation is necessary for multiobjective optimization.

Multiobjective Optimization

An example is presented to demonstrate the capability to optimize the structural response resulting from several disciplines interacting simultaneously. Figure 12 (Ref. 13) shows a candidate composite structure optimized for single and multiobjective functions. The structure is made of graphite/epoxy composite with a fiber volume ratio of 0.5. The structure is first optimized for displacement amplitude, weight, and cost separately. The structure is then optimized for the displacement amplitude, weight, and cost simultaneously. The design variables in all cases are ply orientations and stiffnesses.

The results showing the initial and optimum objective values are included in Fig. 12. The initial values of all three objective functions are shown as 100%. The percent change in each of the three objective functions is then shown for three different optimization runs, each run for optimizing one objective function separately. The right-most bars in Fig. 12 show the optimum objective functions when all three objective functions are optimized simultaneously. The best design within the specified constraints is obtained when the multiobjective function is used. It is interesting to note that the multiobjective optimization includes the optimum of all three individual optimization cases: 1) 75% reduction in first-frequency amplitude, 2) 25% reduction in weight, and 3) 50% reduction in cost.

Integrated System of Multidisciplinary Analysis Optimization

A nonlinear materials behavior simulator,[12] a finite element code,[14] and the coupled multidiscipline code CSTEM[10] were integrated for simulating the fatigue behavior of a multilayered hot and wet composite panel acoustically excited by an adjacent vibrating hot panel (Fig. 13). This is typical of aircraft components subjected to acoustic vibrations.

Figure 14 shows the acoustic fatigue life results for three different laminate configurations of the composite panel. The results are based on a coupled composite-material/hygral/thermal/structural/acoustic simulation.[15] Figure 14 shows that the fatigue life of the acoustically excited panel can be increased substantially (at least by two decades) by placing off-axis plies on the outer surface of the laminate. The important point is that the coupled multidisciplinary response of composite structures can be computed to yield superior designs. Expected failures in real-life service environments have been avoided because the analysis captures the various multidiscipliary coupling effects (interactions).

Coupled Material-Behavior/Fabrication-Process Tailoring

The fabrication process of a composite laminate can be tailored for desired optimum single discipline or multidiscipline objectives using a metal matrix laminate tailoring code (Fig. 15, Ref. 16). The bar chart results in Fig. 15 show the laminate characteristics (extensional stiffness, compressive load capacity, bending stiffness, and bending load capacity) that can be attained by optimizing for individual stiffness or load maximum as well as for concurrent stiffness/load maximum improvements by more than 50%.

Sensitivities Using Probabilistic Methods

The sensitivities of the effective stress for a second-stage turbine blade of the Space Shuttle main engine at two different blade locations were assessed via a probabilistic structural behavior simulation.[17] Figure 16 shows the blade model and probabilistic distributions of the blade geometry, material, and mechanical/thermal loads.

The cumulative probability for the effective stress at two different blade locations is included in Fig. 16. The important (sensitivity) factors for five dominant variables were found to be different and with different importance ranking at different blade locations. The sensitivity factors in Fig. 16 are listed in decreasing order of importance of their effect on the effective stress. These are the off-diagonal terms in the array. The deterministic structural analysis does not provide the sensitivity information that can be crucial in designing structures effectively. The important points are as follows.

1) The material/structural behavior is modeled based on real-life uncertainties in all the design variables.

2) The structural reliability is evaluated.

3) The dominant factors that influence reliable designs are identified.

Coupled Materials/Structures/Fracture/Probabilistic Behavior Simulator

A progressively more inclusive integration of the various discipline-specific simulators is made possible with the existing infrastructure at NASA Lewis Research Center. An ex-

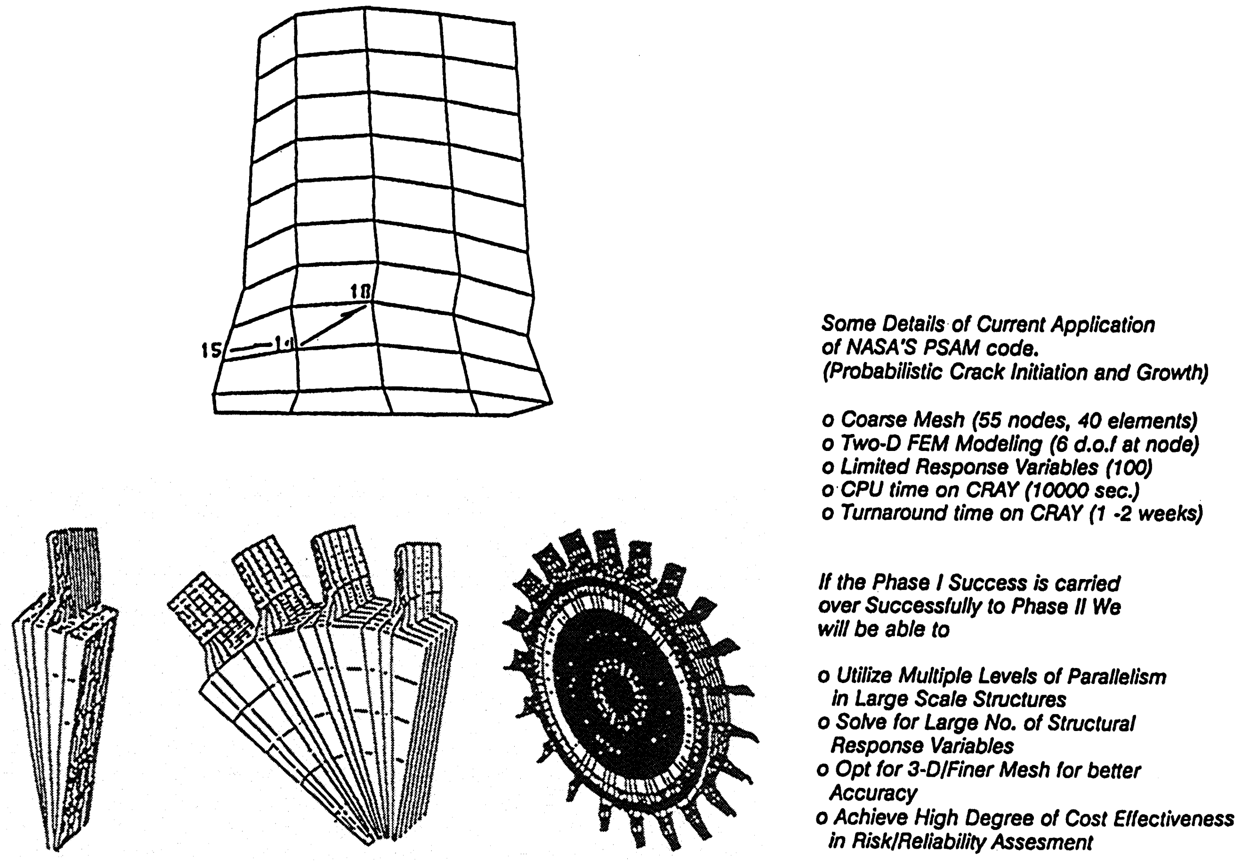


Fig. 17 Criterion 2 phase I results score: 25.

Table 2 Multidiscipline coupling through optimization

Discipline response	Initial	Thermal	Discipline optimization, structural			Acoustic	Electomagnetic
			Vibration	Cost	Weight		
Thermal							
Maximum temperature, °F	264.0	**218.0**	288.0	262.0	272.0	224.0	272.0
Structural							
Vibration frequency, cps	——	——	——	——	——	——	——
Fundamental	77.0	133.0	**63.0**	86.0	68.0	129.0	71.0
Cost, $	29.10	40.69	29.10	**21.30**	40.69	29.10	40.69
Weight, lb	0.44	0.31	0.44	0.52	**0.31**	0.44	0.31
Acoustic							
Emitted noise, dB	95.9	87.1	99.7	94.1	97.8	**86.8**	97.1
Electromagnetic							
Reflected power, %	81.3	70.5	81.3	85.4	70.5	81.3	**70.1**
Structural							
Second vibration frequency, cps	270.0	415.0	210.0	295.0	241.0	407.0	250.0
Third vibration frequency, cps	544.0	594.0	460.0	561.0	492.0	584.0	497.0
Maximum radial displacement, in.	0.0065	0.0065	0.0130	0.0075	0.0090	0.0039	0.0095
Maximum radial stress, ksi	7.8	10.4	8.9	12.0	17.5	13.9	14.7
Tailoring			$100 < f_2, f_3$				
Constraints	——	——	<1000	——	——	——	——
Design variables							
Ply thickness, %	0.25/0.5/0.25	0.24/0.2/0.56	——	0.15/0.7/0.15	0.25/0.2/0.55	——	0.1/0.02/0.07
Ply orientations	30/0/30	60/0/−5	61/0/62	——	——	−4/0/−2	——

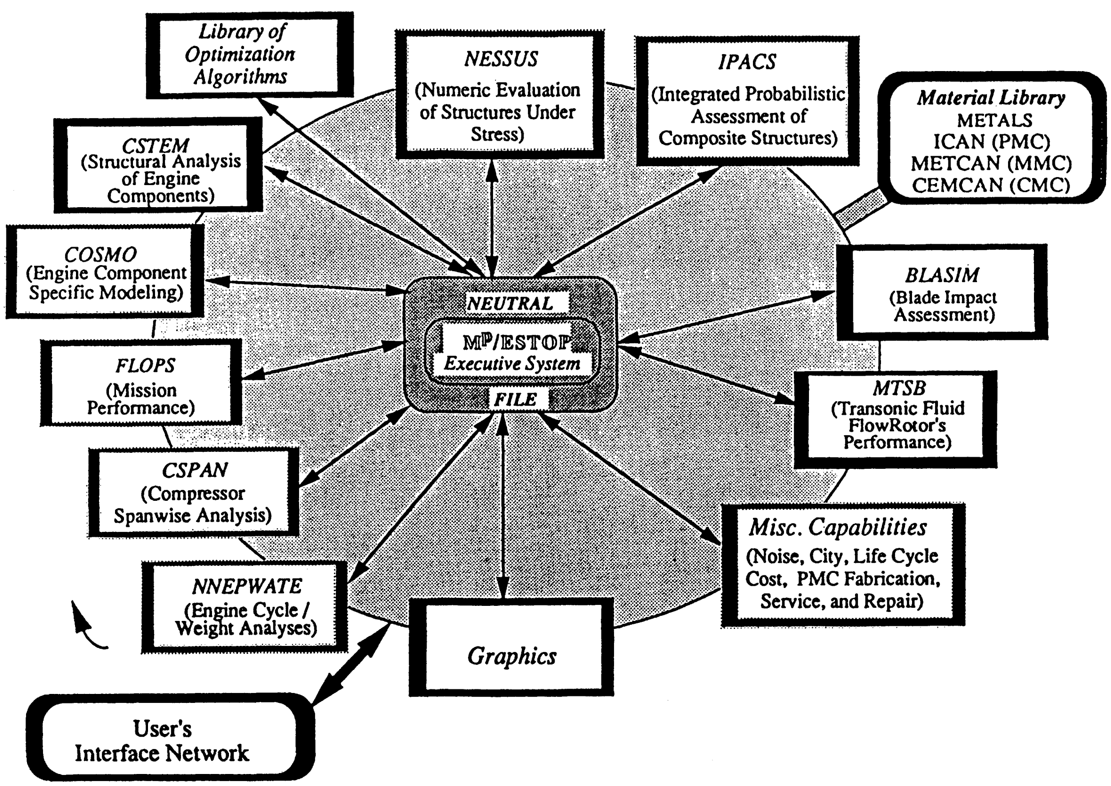


Fig. 18 M^P/ESTOP architecture block diagram.

ample of probabilistic crack initiation and growth for a rotor blade is shown in Fig. 17.

The results of the coupled materials/structures/fracture/probabilistic behavior of the rotor blade, including interactions resulting from uncertainties in various design variables at their lowest levels (identified as primitive variables), are included in Fig. 17. The direction of the fracture path is determined, not by a specific analysis, but by the previously mentioned coupled effects.

The success in applying coupled materials/structures/fracture/probabilistic simulation for structural components enables the utilization of multiple levels of parallelism in large-scale structures. It will then be possible to solve for large number of structural response variables. A high degree of cost effectiveness in risk/reliability assessment will be achievable. For better accuracy, three-dimensional finer meshes can be modpeled. It is important to note that the coupled simulation assures simultaneous robust and reliable designs, which is very difficult if not impossible to achieve by state-of-the-art simulation methods.

Multidiscipline Sequential Optimization

An integrated simulator for propulsion systems will entail a very large number of coupled (interrelated) variables. In addition to coupled multidiscipline simulators that were discussed earlier, innovative approaches are needed to reduce the dimensionality of the system description while still retaining the essential system behavior. The viable approaches include

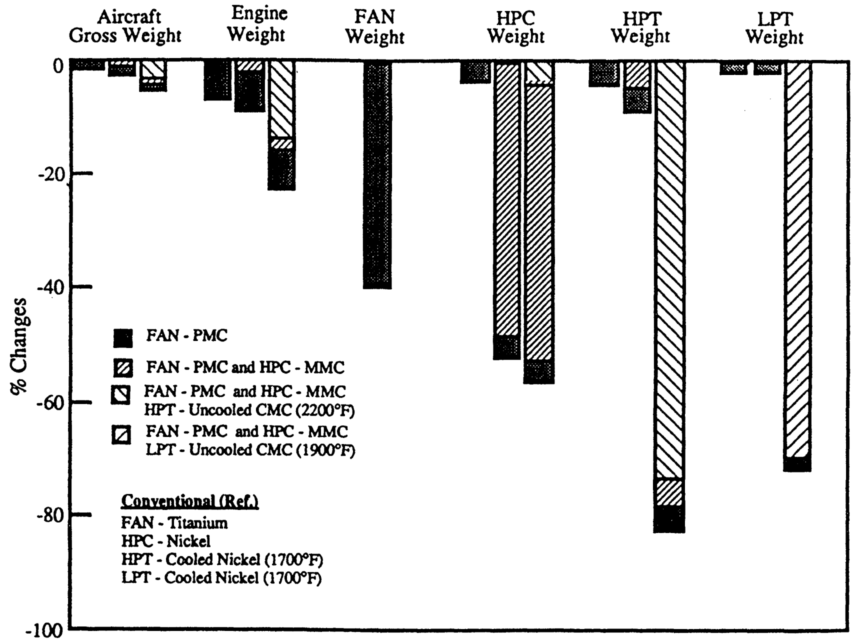


Fig. 19 Weight benefits of PMC over titanium for fan, MMC over nickel for compressor, and uncooled CMC over cooled nickel for turbine.

sequential iterations between disciplines, specially derived system matrices, and coupling at the fundamental equation level. The *coupling across disciplines in a concurrent multidisciplinary* formulation can be represented by coupling relations. The coefficients (elements) in these relations define the coupling of a specific variable from one discipline with respective variables from interacting disciplines.

Perturbation of the variables in the coupling relations provides a measure of the sensitivity of the interacting disciplines to this perturbation. An up-front quantification of this relationship sensitivity enhances the computational simulation in several respects: 1) scoping the degree of coupling, 2) identifying the interacting disciplines, 3) resolving time/space scales, 4) selecting time/space scale for loosely coupled interacting discipline intervention during the solution processes, 5) deciding on a solution strategy, and 6) imposing convergence criteria.

At least four different methods can be used for defining and deriving the off-diagonal sensitivity relations. These are 1) heuristic, based on available traditional single discipline approaches and expert opinion; 2) multidiscipline sequential optimization, based on determining the primitive variable for optimum response within a single discipline, determining the response for optimized primitive variables for all coupling disciplines, and repeating the process for each discipline of interest; 3) probabilistic evaluation, by determining the sensitivities of multidisciplinary response to interrelated primitive variables; and 4) fundamental-coupled formulation, based on mixed-field finite elements (recent research activity), which account for the physical coupling in the primitive equations.[18] These results will then be processed to compute the coupling coefficients of the specialty multidisciplinary matrices. A simple case is shown in Table 2, where the coupling terms were evaluated at the optimum of the discipline noted in the bold typed values.

A current activity at NASA Lewis Research Center for multidisciplinary optimization is summarized in Fig. 18. Note that M^P/ESTOP denotes multifaceted engine structures optimization, where P to date is 7 as follows: 1) multimaterial, 2) multilevel, 3) multiscale, 4) multicomponent, 5) multidiscipline, 6) multioptimization and 7) multialgorithm. Multialgorithms are used in a cascading manner to obtain improved optimum in multidiscipline optimizations.[19] Preliminary, but typical, results from this activity are summarized in Fig. 19 (Ref. 20). The notation in Fig. 19 is as follows: high-pressure compressor (HPC), high-pressure turbine (HPT), low-pressure turbine (LPT), *polymer matrix composite* (PMC), *metal matrix composite* (MMC), and ceramic matrix composite (CMC). As can be seen, M^P/ESTOP can be used for the entire engine, which demonstrates the computational effectiveness of soft coupling of integrated discipline specific computer codes. The important observation to note from Fig. 19 is that vehicle, engine, and subsystem-type metrics are obtained by the use of M^P/ESTOP. That type of information is very useful, particularly at the preliminary design stages. The author considers M^P/ESTOP-type capabilities the wave of the future.

Concluding Remarks

Computational simulation combined with multidiscipline optimization is a natural and cost-effective method to evaluate multidiscipline coupling. Concurrent development of multidisciplinary computer codes provides the infrastructure to computationally simulate multidiscipline coupling. The coupling across disciplines in a concurrent multidisciplinary formulation can be represented by coupling relations arranged in array form. The diagonal coefficients in these coupling arrays can be determined by various techniques including sequential optimization, probabilistic approaches, and coupled fundamental formulations. The results show that coupling effects of multidiscipline or multiobjective optimization can be modeled using existing codes. The coupling methods combined with other suitable infrastructure can be used to develop the off-diagonal terms for the entire system. Multidiscipline computational simultation with multiobjective multialgorithm optimization by soft-coupling is definitely the wave of the future.

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