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INTERDISCIPLINARY TECHNOLOGY

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Interdisciplinary Approach to Propulsion System Simulation

The "computational test-cell" will enable the incorporation of new methodologies, such as concurrent engineering and probabilistic methods, into the propulsion design process. This will provide the capability to conduct credible, interdisciplinary analyses of new propulsion concepts and designs.

Probabilistic methods can be used as the basis for reliability-based design. Recently methods have been devised that provide the capability of simulating the performance of propulsion systems at several levels of resolution. These methods make it possible to quantify uncertainty and to establish confidence bounds for the calculated values.

The introduction of reliability-based design methodology along with probabilistic analyses will provide a tool to reduce the design space for new systems and to reduce our dependence on hardware testing for proof-of-concept and system integration demonstrations. The resulting simulations will reduce the need for testing and identify potential operational problems early in the design process.

This capability will make it possible to compute the expected performance, stability, reliability, and life of propulsion components, subsystems, and systems at design and off-design conditions, to bring life cycle cost trade-offs early into the design process and to determine optimum designs to satisfy specified mission requirements.

Physics Modeling

The analysis of propulsion phenomena involves a combination of disciplines including fluid mechanics, thermal sciences, structural mechanics, material sciences, combustion theory and controls theory. The degree of resolution within an analysis is determined by the magnitude of local effects, the extent of their region of influence, and the dynamic time scales of the appropriate physics relative to the dynamic scale of the system phenomenon being analyzed. Often the limiting factor will be the available computer power (speed and memory capacity). The analyst must determine which terms in the governing equations to retain and which to ignore so as to achieve the maximum level of fidelity within the computational constraints.

The coupling of the disciplines and component codes involves the subdivision of a complete system, e.g., an aircraft engine, into a series of subsystems, e.g., inlet, compressor, combustor, turbine, and nozzle. It is convenient to define a hierarchy of multi-disciplinary simulation modules for each subsystem ranking from relatively simple time and space "averaged" analysis methods (level I) to complex three-dimensional, time-accurate analysis methods (level V).

Level I: Engine system performance model. This model is basically a thermodynamic model which calculates the system efficiency based upon engine configuration and component efficiencies. It allows rapid evaluation of various engine concepts.

Level II: Engine system dynamics and controls model. This model is basically a one dimensional flow path model, with simplified structural elements, controls, and other disciplines. It uses component performance information, design geometry information, and dynamic information in order to calculate engine thrust and weight as well as system transient response in order to analyze operability problems and devise control strategies to handle them.

Level III: Space and/or time-averaged engine system model. This model is basically a two-dimensional (i.e., axisymmetric) fluid model. It utilizes axisymmetric, coupled discipline models in an engine system environment in order to relate component boundary conditions (primarily input/output conditions) to overall system boundary conditions in order to simulate component interactions. This is also the basic level about which the "zooming" process is constructed. It will be a transient model and address all problems from level II but, in addition, provide more detailed geometry information.

Level IV: Space and/or time averaged sub-system (or component) models. These models are basically three dimensional. They are multi-discipline models which are coupled in ways which are compatible with the physics of the component model, but are still averaged over smaller time and space scales. These models must also be post-processed in order to connect with the level three engine system model in the "zooming" process.

Level V: Three-dimensional, time-accurate component models. This level of simulation basically consists of a fully three-dimensional, time-accurate simulation of all physical processes on a component-by-component basis. This is the most complete level of physical approximation.

Dicsipline Coupling

Propulsion phenomena are inherently multi-disciplinary (i.e., the true system response is the coupled effect of all the participating disciplines and the aggregate of the system components' responses and interactions). Present analyses (and experiments) tend to focus on single-discipline aspects of the phenomena within a local region (e.g., a single component). Using suitable approximations, these analyses are sometimes extended to a propulsion subsystem or, in rare cases, the complete propulsion system.

Recent advances in computational fluid mechanics, computational structural mechanics, computational materials science, computational controls, and computer science and technology make it feasible to consider the development of a "computational test-cell" for propulsion that would allow for comprehensive simulation and analysis of entire propulsion concepts and designs before committing to hardware.

For computational simulation to be credible, it must include efficient multi-disciplinary coupling. In the case of multi-disciplinary simulation of dynamic phenomena, the time scales associated with various aspects of the phenomena have to be considered. In an engine interacting phenomena, such as surge, stall, flutter, component and system dynamics, low and high cycle fatigue, and takeoff and landing operations occur within widely varying time intervals. The computational procedures and the "clock cycle" of a multi-disciplinary simulation have to accommodate these vast differences in time scales. The simulation clock cycle has to be consistent with the available computational power and, in the case of animated graphic representation, the perception rate of the human visual capability.

Implementing coupling in the required numerical simulation, analysis, and optimization is a tremendous challenge because of the potentially very large number of interrelated variables and the very large number of iterations that can result from general-purpose algorithms. A hierarchical approach that can reduce the dimensionality of the system description while still retaining the essential system behavior is needed. There are a variety of techniques that can be used for coupling discipline variables for propulsion components, subsystems, and systems. These include sequential iteration between disciplines, specially-derived system matrices, and coupling at the fundamental equation level. In NPSS, all three methods will be applied to the filtered Navier-Stokes equations and the progressively substructured structural mechanics formulations. Relationships (i.e., sensitivities) will be derived for use in optimization algorithms that are streamlined for the multi-disciplinary, multi-component application.

The coupling across disciplines in a concurrent multi-disciplinary 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 (Fig. 6). Perturbation of the variables in the coupling relations provides a measure of the sensitivity of the interacting disciplines to this perturbation. A priori description of this sensitivity relationship 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.

Analysis Fidelity

Attempting to resolve all of the length and time scales that are present in the fluids and structures of the engine is impractical, even on high performance computers. Therefore, a rational approach for identifying and resolving the critical scales is needed. Approaches that have been shown to be effective for single component analyses will be extended to the simulation of coupled components and entire engine systems. Approaches will be developed to allow selected components to be resolved to a greater level of detail than others. Utilization of the zooming approach will allow the interconnection of a series of multi-discipline simulations in which a single or small number of modules are simulated with very accurate methods, perhaps level IV or V, while the remainder of the subsystems are implemented with simple methods, perhaps level II or III. This focusing or "zooming" in on a particular component will allow for a more thorough analysis of that subsystem in a complete multi-discipline system format without having to completely simulate the entire system at the same detailed level.

For example, studies of compression system stability will require a detailed treatment of the compression system to be coupled to lower-resolution treatments of the fan, combustor, turbine, and nozzle with the appropriate boundary conditions to represent the inter-component interactions (Fig. 5). This "zooming" capability will permit the analyst to capture relevant physical processes throughout the engine in a computationally-tractable manner and will allow the analysis to be used on a routine basis for design assessment and optimization. Thus, this approach will be much more cost effective and should provide an attractive approach for overall system performance optimization. The actual interface algorithms used in this zooming approach will range from the direct coupling approach described above to one involving the interface of time- and space-averaged parameters. With this approach, special emphasis can be placed on the effects of interface sensitivities between two subsystems in an entire system.

Computational Simulation

Digital simulation of aerospace propulsion system behavior has been in existence for many years. The earliest simulations were developed in the seventies. The performance and reliability of engine systems depend on the dynamic interaction of their subsystems which, in turn, depend on the dynamic interaction of their respective components. Interaction phenomena of importance include flutter, rotor instability, fatigue, flow separation, nonuniform combustion, blade containment, and noise suppression. The determination of aero-thermodynamic system performance has traditionally relied on prototype tests while structural reliability has been calculated from field data. This experience has been used to develop simulation techniques that employ varying degrees of approximation to model and compute the aero-thermodynamic performance and structural reliability of new designs. In general, these simulations can be divided into two classes, depending upon the time dependance.

Steady state simulations are normally used by design engineers in order to assess design trade-offs. Here the emphasis is on ease-of-use by the designer and, in particular, allowing the designer to include "company lore" or company expertise in the design. Depending upon the use of the design system (i.e., whether it is for conceptual design, preliminary design, detailed design, or final design) there will be more or less fidelity included in the simulation. Steady-state simulations are used for design points analysis, with allowances for off-design performance. In the latter design stages, steady-state simulations can be used to develop control system schedules and to provide estimates of engine system life.

Dynamic simulations are used after the engine is designed in order to develop control laws/logic and to determine the limits of stable engine operation. Obviously, if the simulation calculations can be speeded up, more detail (i.e., spatial and temporal resolution) can be included in the simulation model. During control system hardware and software implementation, there is a need for a real-time engine simulation that can be operated with the control system in a "closed-loop" fashion.

Dynamic simulations are also used to study cases when the engine behaves differently in the field from what was envisioned in the design phase, or as uncovered in the testing of the engine before it was installed into service. These simulations can be particularly valuable when ground-based experimental facilities are not available to simulate the in-flight conditions under which the unusual behavior was observed. Obviously the more accurate the simulations, the more their value.

The development of an engine simulation capability will begin with existing Level II dynamic engine system models of aerothermal and structural behavior. Level IV aerothermal and structural simulations will be used to generate the required component parameters and maps for the Level II engine models. Then, methods for improving the parametric representation of the components will be investigated so that the significant phenomenon observed from detailed analyses can be represented in the engine model.

The initial simulations involving Level II aero and structures codes will investigate the thermal lag between changes in the engine operating conditions and the heat transfer effects on the structure. Thermal strains resulting from the changes in the temperature of the structure affect the secondary cooling flow passages and tip clearance flow in the components. These effects must be accounted for in the aero codes and will result in a change in the computed engine operating conditions.

The Level IV aerodynamic simulation model that will serve as the basis for the integrated propulsion system model will be the Adamczyk average-passage formulation which consists of the filtered forms of the Navier-Stokes and energy equations. This model was designed to resolve only those temporal and spatial scales that have a direct impact on the relevant physical processes. The effects of the unresolved scales, which appear as body forces and energy sources in the equations, are estimated through semi-empirical relations, based on experiments or high-resolution numerical simulations. The results from the lower-resolution analysis appear as boundary conditions for the high-resolution model. Initially, this model will be applied to the study of a compression system and its performance, stability, blade vibration, and noise generation. Since the methodology applies to the fundamental fluid flow equations, it will then be extended to the other propulsion components.

The structures modeling will be aimed at developing a comparable computational capability that will provide a means to traverse multiple scales of spatial resolution with a minimum number of variables at each level. In this way, an analysis can proceed from a blade to a rotor sector to a rotor to an engine core to the complete engine. The resulting system model will have a minimum number of degrees of freedom consistent with the objectives of the analysis which will minimize the computational requirements. This methodology will be applicable to the solution of linear and incremental nonlinear analysis problems. This capability will be achieved through the formulation and implementation of a progressive substructuring ("telescoping super-elements") technique within the mixed-iterative finite element method framework and associated MINUTES computer code and within the boundary element framework and associated BEST3D computer code.

Computing Platform Portability

It is the intention of the NPSS to take advantage of existing codes to the extent possible, while at the same time maintaining the flexibility to utilize emerging massively parallel computing hardware platforms. The architecture envisioned ustilizes shared memory programming paradigm and standard software tools and programming language extensions. The programming will be independent of hardware architecture.

Within the computing system, the nature of the coupling between the computing system components (processor, memory, communication) will depend upon the engine system component codes and single discipline codes required to compute the desired engine attributes. Therefore, the selection/development of appropriate processor I/O software, compilers, networking protocols will be accomplished in conjunction with the development of engine system and discipline (i.e. application) codes.

The NPSS technology project can develop and demonstrate many key, enabling technologies for aerospace propulsion systems design, analysis, and optimization. However, to be successful, several things must take place:

Effective inter-disciplinary teams must be established to define, advocate, and implement technical solutions.

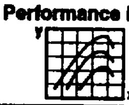
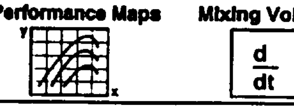
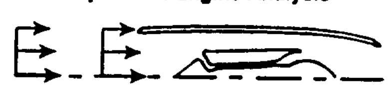
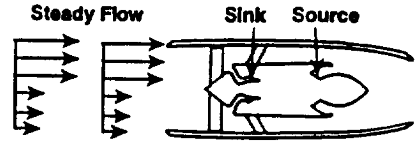
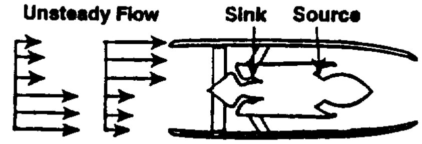
Coordination and a balancing of efforts among the inter-disciplinary engine system activities (physics, algorithms, models, codes) and the inter-disciplinary computer system activities (architectures, software tools,..) must be maintained so as not to push either activity ahead of the other.

This suggests a strong requirement for effective project management to ensure that the available funding and skilled staff are effectively used to address the needs.

NPSS Goal

- Reduce life-cycle costs by advancing system analysis capability through high-fidelity computational simulations by
    - Higher level of concurrent engineering
    - Rapid evaluation of effects of new and novel concepts on system performance
    - Early risk assessment
    - Early operability studies
    - Rapid evaluation of field problems
    - Assessment of performance degradation

NPSS LEVELS OF MODELING FIDELITY

LEVEL 1: ONE DIMENSIONAL STEADY-STATE	One Dimensional Engine System Analysis Performance Maps 
LEVEL 2: ONE DIMENSIONAL TRANSIENT	One Dimensional Transient Engine System Analysis Performance Maps Mixing Volumes 
LEVEL 3: AXISYMMETRIC/TWO DIMENSIONAL QUASI-STEADY-STATE	Axisymmetric Engine Analysis 
LEVEL 4: THREE DIMENSIONAL QUASI-STEADY-STATE	Three Dimensional Engine Component Analysis Steady Flow Sink Source Fan Analysis 
LEVEL 5: THREE DIMENSIONAL TRANSIENT	Three Dimensional Transient Engine Component Analysis Unsteady Flow Sink Source Fan Analysis 

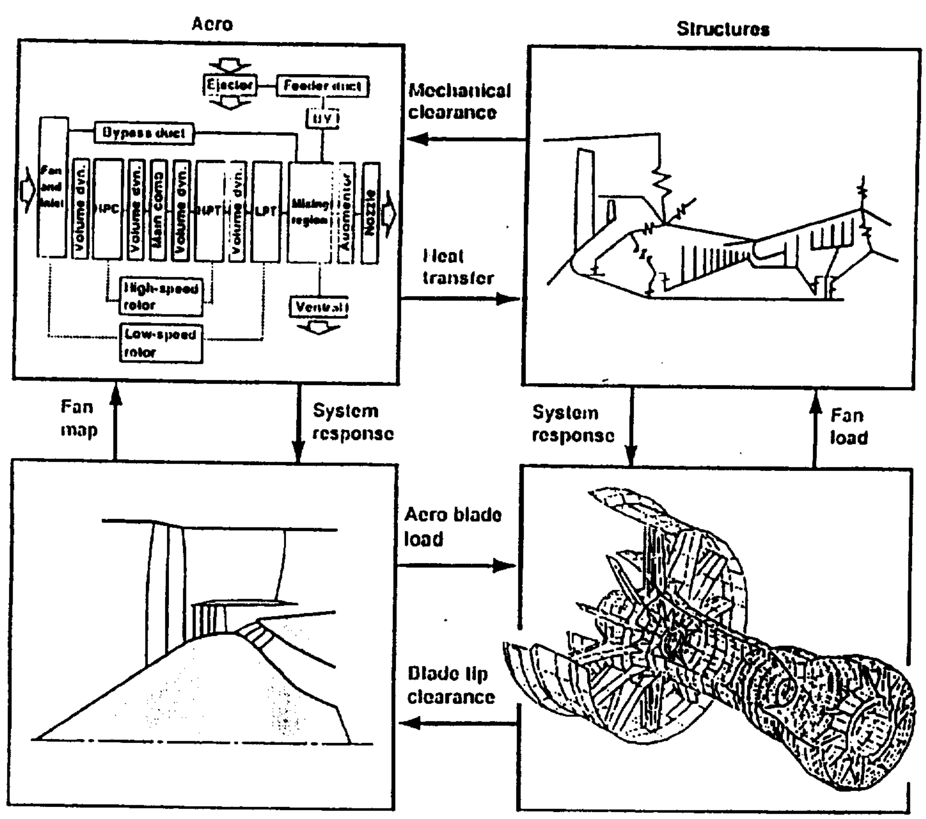
Coupled-Multi-Discipline Representation for Aerospace Propulsion Systems

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

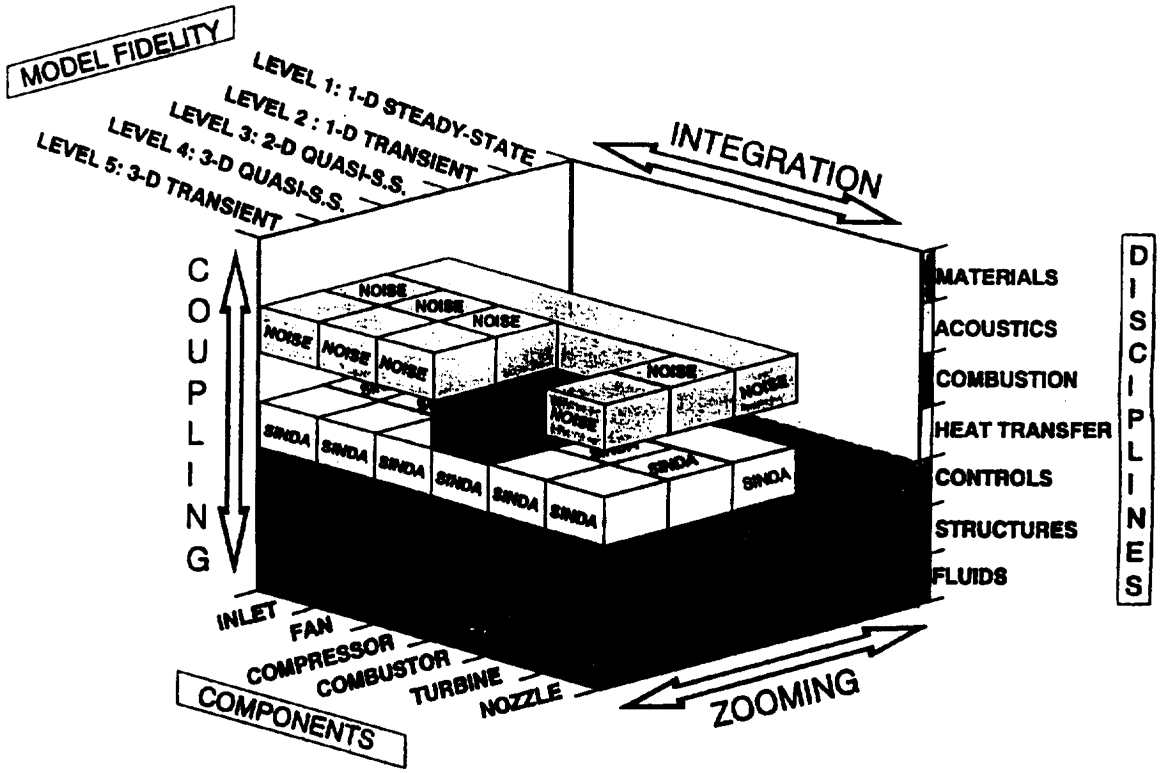
System response variables — System definition/characteristics and coupling relationships — System development and service parameters

A	Aero	F	Fabrication
T	Thermal	P	Performance
S	Structural	C	Cost
M	Material		

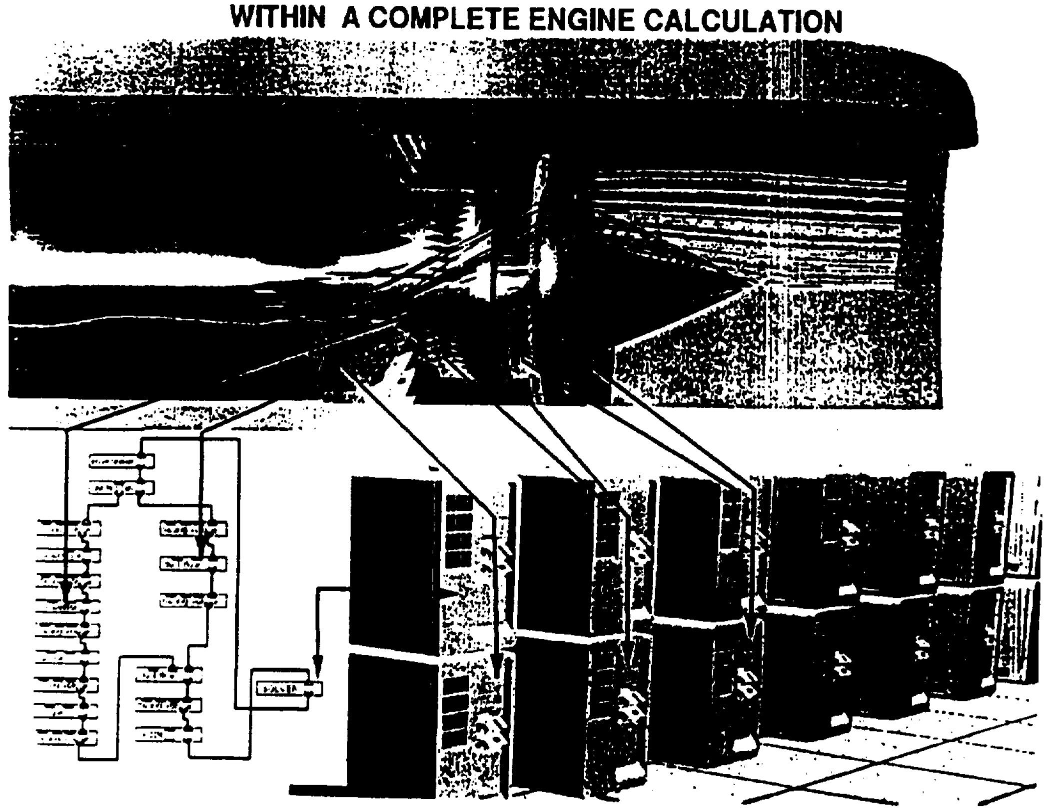
NPSS Models



MULTIDISCIPLINARY SIMULATION OF PROPULSION SYSTEMS

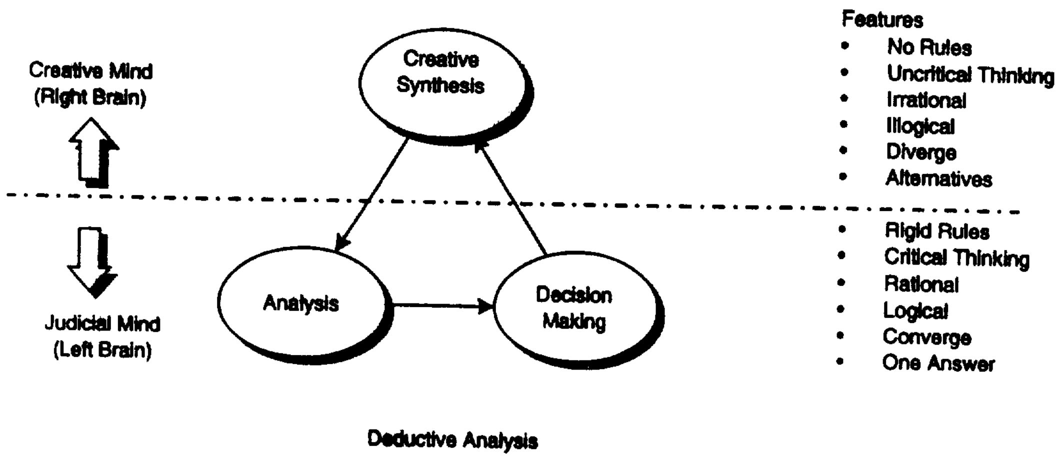


TESTBED SIMULATION OF MULTIPLE COMPONENTS WITHIN A COMPLETE ENGINE CALCULATION



Koen (1985): "...it is the engineering method or design process, rather than the artifacts designed, that bind *all* engineering disciplines together and defines the engineer."

The Engineering (Design) Process



Engineering (Designers/Synthesizers) = Engineering Science Technicians (Analysts)
• Industry Needs Both •