Technology Drivers in the Development of CAMRAD II

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Technology drivers in the development of the comprehensive helicopter analysis CAMRAD II are reviewed. The issues discussed include flexibility of configuration model and solution procedure; expandability; mathematical model of kinematics, dynamics, and response; transportability; ease of use and productivity; and demonstrated capability.

Introduction·

CAMRAD II is an aeromechanical analysis of helicopters and rotorcraft that incorporates a combination of advanced technology, including multibody dynamics, nonlinear finite elements, structural dynamics, and rotorcraft aerodynamics. For the design, testing, and evaluation of rotors and rotorcraft – at all stages, including research, conceptual design, detailed design, and development – CAMRAD II calculates performance, loads, vibration, response, and stability – with a consistent, balanced, yet high level of technology in a single computer program – applicable to a wide range of problems, and a wide class of rotorcraft. Such capability is essential for helicopter problems, which are inherently complex and multidisciplinary.

CAMRAD II uses a building-block approach to achieve flexibility in the model of the dynamic and aerodynamic configuration. Hence it can model the true geometry of a rotorcraft, including multiple load paths (such as a swashplate and control system, lag dampers, tension/torsion straps, and bearingless rotors); vibration control devices (such as pendulum absorbers or active control); arbitrary elastic axis and arbitrary hinge order; drooped and swept tips; and dissimilar blades. CAMRAD II provides a powerful analysis capability, including advanced rotor aerodynamics; rigorous kinematics and dynamics (with consistent structural loads and dynamic response, and general interfaces between aerodynamic and structural dynamic components); and general transient solutions. For ease of use a shell is provided to build typical rotorcraft and rotor models, while the core input capability always gives complete flexibility to define and revise the model. A range of components and modeling options makes it a practical engineering tool, allowing the best balance of efficiency and accuracy to be found for a particular problem. CAMRAD II offers a common tool among organizations, and a design for growth that makes it an appropriate platform for future developments, for continuing access to new technology.

CAMRAD II performs a nonlinear dynamic/static analysis of an aeromechanical system. Flexibility and generality of the system configuration are obtained by assembling standard components with standard interfaces, and solving the system by standard procedures. The basic approach of the analysis is to make no approximations (beyond time and space discretization) at the highest levels, handling exact (nonlinear and time-varying) equations. The analysis solves differential, integral, static, and implicit equations for the motion of the system, and evaluates required output quantities from the response. The trim task finds the equilibrium solution (constant or periodic) for a steady state operating condition. The transient task integrates the equations in time for a prescribed excitation. The flutter task obtains and analyzes differential equations, linearized about trim, perhaps with quasistatic reduction for a stability derivative model.

For configuration generality, CAMRAD II splits the system into pieces – physical pieces (components and interfaces) and logical pieces (solution procedure) – with connections between. The components available include structural dynamic, aerodynamic, and differential equation models. These system pieces constitute the core analysis, providing a flexible, building-block oriented modelling capability. In addition, the analysis has a shell that constructs the core input for typical rotorcraft and typical problems. The shell constructs the input for arbitrary one-rotor or two-rotor aircraft; in free flight or a wind tunnel; with N-bladed rotors having articulated, hingeless, teetering, gimballed, or bearingless root configurations, including a swashplate model. The aerodynamic model includes a sophisticated wake analysis to calculate the rotor nonuniform induced-velocities, using rigid, prescribed or free wake geometry.

A comprehensive helicopter analysis must calculate performance, loads, vibration, response, and stability. The multidisciplinary nature of helicopter problems means that similar models are required for all of these jobs. It follows that a comprehensive analysis must have a rotor wake model; account for drag and stall of the rotor blades; include nonlinear dynamics of the rotor and airframe; and model the entire aircraft. The analysis must perform the trim, transient, and flutter tasks, as illustrated in figure 1. The analysis solves differential, integral, static, and implicit equations for the motion of the system; and then evaluates required output quantities from the response. The trim task obtains the equilibrium solution for a steady state operating condition. The operating condition can be free flight, including level

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flight, steady climb or descent, and steady turns; or constrained, such as a rotor in a wind tunnel, with typically the thrust and flapping trimmed to target values. It is usually necessary to identify the control positions and aircraft orientation required to achieve the specified operating condition. The trim task obtains the steady or periodic response of the system. For a rotorcraft, an important modelling choice is the wake model: uniform inflow, nonuniform inflow with prescribed wake geometry, or nonuniform inflow with free wake geometry. The transient task numerically integrates the equations in time (from the trim solution), for a prescribed excitation. The flutter task obtains differential equations for the system, linearized about trim (probably by numerical perturbation). The linear equations can represent the full dynamics of the system, or a quasistatic reduction of selected variables can be performed, including a stability derivative representation. The response can be calculated for time-invariant equations (perhaps averaged), or for periodic equations.

Experience with early codes such as CAMRAD/JA defines the requirements for a modern comprehensive analysis of helicopters. Flexibility of configuration model and solution procedure is essential. The analysis must handle complex configurations, including unusual load paths and interactions, with many subsystems. The analysis must be expandable, which requires separate specification of the configuration, aeromechanical models, and solution procedures. The mathematical model of the kinematics, dynamics, and response must include nonlinearities (structural, aerodynamic, and kinematics); and arbitrary large motion, including rigid body motions and large rotations of components relative to each other. The mathematical model can not be limited to just the equations and interfaces of structural dynamics. The analysis must be transportable. The analysis must be easy to use, especially for normal configurations. The capability of the analysis must be demonstrated through applications.

This paper reviews the technology drivers in the development of the comprehensive helicopter analysis CAMRAD II – the factors that shaped the product. The issues discussed include flexibility of configuration model and solution procedure; expandability; mathematical model of kinematics, dynamics, and response; transportability; ease of use and productivity; and demonstrated capability.

Flexibility of Configuration Model

A modern comprehensive analysis must be able to analyze arbitrary configurations – whatever the designers can invent. Analyses such as CAMRAD/JA are characterized by fixed geometry and dynamic models, and fixed aerodynamic models. Hence a new rotor or helicopter configuration requires new development of the equations. With such an approach, the analysis capability can lag invention by a decade or more. Also, the structural dynamic and aerodynamic models are mixed, so it is not possible to change one without considering the other.

The requirement for a modern analysis is that the system configuration be defined and changed by input to the analysis. It should not be necessary to change the code as long as the required physics are available. Hence the physical and mathematical models must be separated from the definition of the configuration. Also, the structural dynamic and aerodynamic models must be separated.

CAMRAD II uses a building-block approach to achieve flexibility in the model of the dynamic and aerodynamic configuration. Flexibility and generality of the system configuration are obtained by assembling standard components with standard interfaces, and solving the system using standard procedures.

For configuration generality, CAMRAD II splits the system into pieces, with connections between. Table 1 summarizes the environmental, physical, and logical pieces available to construct the system. The environmental pieces provide a standard description of the system operation. The physical pieces correspond to the physical description of the system, and produce the system equations. The logical pieces define the procedure for solving the system equations. Thus a standard description of components, interfaces, and solution procedures is implemented. These system pieces constitute the core analysis, providing a flexible, building-block oriented modelling capability.

The physical pieces define the equations that describe the system (figure 2). Components contain the physics of the model, performing all calculations for the system. Components have input f_{nj} and output x_{nj}, each either structural dynamic or input/output kind. An interface connects two or more components. The interface type can be structural dynamic or input/output. The input and output system pieces provide external connections to the system. Associated with each physical piece are certain variables and equations:

components: degrees of freedom ξ_n and motion equations

interfaces: constraint variables f_l and constraint equations

input: input variables u_m

output: output variables y_q and output equations

Components perform all computations associated with the physics of the model of the system (except the structural dynamic interface). So components are the focus of modelling issues, including the empiricism and approximations needed for a practical model of many real systems. Development of an improved model requires the development of a new component, which will fit into the existing analysis framework. Table 2 lists the components available in Release 1.1.

A standard form is defined for all components. Structural dynamic components have common characteristics: rigid body motion and frames; mass, hence inertial and gravitational forces; and structural dynamic interfaces. Thus there is a common implementation for structural dynamic components, which then differ primarily in their representation of the elastic motion. This implementation provides standard interfaces for connections with aerodynamic components; applied loads, sensors, and a spring/damper/actuator model; and linear and angular joints. The standard spring/damper model has linear and nonlinear terms, and can include an offset or force actuator (a displacement actuator is obtained from a controlled joint).

The standard joint model is defined with sufficient flexibility to implement all joint configurations required. A joint can consist of one to three (or no) linear variables, and one to three (or no) angular variables. The linear motion can represent a slide (or prism, or linear hinge), plane, or space joint. The angular motion can represent a hinge (or revolute), universal, or ball (or spherical, or pinned) joint. The linear and angular motion can be combined to model a screw, rack and pinion, transmission, and other mechanical devices. Each joint variable can be prescribed, controlled, or a degree of freedom.

There are other kinds of components as well, in particular aerodynamic models. An aerodynamic component typically models a wing or body, which is a surface moving through the air. Interfaces between the structure and the air occur at discrete points on the surface (collocation points). A collocation point is a connection on a structural dynamic component, the interface involving velocity, position, and force.

The standard component description must accommodate all kinds of components, yet the analysis must also handle and use the special characteristics of structural dynamic components. Hence it is not possible to assume that the equations are symmetric, or that they are second order differential equations. In general the component can also have first order, static, and integral equations; and even structural dynamic equations may not be symmetric. It is not possible to assume that the constraint equations are obtained from displacements. In general an input/output interface can involve velocity or acceleration as well. It is not possible to base the component model on a system Lagrangian. Even the structural dynamic components will have explicit constraint forces.

Flexibility of Solution Procedure

The definition of the solution procedure must be just as flexible as the definition of the configuration. Analyses such as CAMRAD/JA are characterized by only one solution method, with little systematic development of solution procedures. Also, the solution procedure and physical models are mixed, so it is not possible to change one without considering the other.

The requirement for a modern analysis is that the solution procedure be defined and changed by input to the analysis. It should not be necessary to change the code as long as the required methods are available. Hence the solution procedure must be separated from the aeromechanical model and the definition of the configuration.

CAMRAD II uses a building-block approach to achieve flexibility in the solution procedure, hence for the logical pieces of the system just as for the physical pieces. The system equations are often large or nonlinear, so in general it is necessary to implement iterative solution methods. The approach used is to define the solution procedure in terms of loops and parts (figure 3). A part solves a subset of the system equations for the response. The physical system (components, interfaces, and output) is divided into parts. Each part has a subset of the system motion, constraint and output equations. Using a method that depends on the part type, the part solves the equations for the corresponding degrees of freedom, constraint, and output variables. A loop iterates between part solutions. Using a method that depends on the loop type, the loop iterates until the converged system solution is obtained.

Expandability

The building-block approach is essential for expandability of the analysis. It is necessary to separate the specification of the configuration, of the aeromechanical model, and of the solution procedure. Otherwise the smallest change involves the entire analysis, and growth becomes increasingly harder as each new feature is added. Release 1.1 developments have demonstrated the expandability of CAMRAD II:

a) Extended use of 3D tables in rigid airframe aerodynamic component.
b) Improved analysis of linear differential equations for flutter task.
c) Constructed programmable component.
d) Constructed helicopter tail boom component.
e) Extended uniform inflow model to include ducted fan.
f) Wing model: generalized wing reference line.
g) Wing model: trailing edge flap characteristics from tables.
h) Wing model: table of prescribed coefficient increments from external aeroacoustic analysis.
i) Wake model: partial induced velocity calculation for external aeroacoustic analysis.
j) Wake model: additional trim loop for high-resolution aerodynamics and partial angle-of-attack.
k) Extended recursive identification in trim loops.
l) HHT numerical integration in transient part.
m) Improved initialization at start of transient.
n) Constructed trim part for time-domain finite element solution (harmonic shape functions).

Starting with most of the theory, such developments typically require about six days work each, including documentation and testing.

Mathematical Model

Approach

The basic approach in the development of CAMRAD II was to make no approximations at the top level of the analysis. This requirement is essential for expandability, since top level approximations and assumptions are very difficult to change.

CAMRAD II has a finite-dimension description of the system, for solution on a digital computer. Components and interfaces introduce spatial discretization, and the solution procedures introduce time discretization. CAMRAD II also assumes that the structural dynamic interfaces are holonomic and independent. No further approximations are made at the top level, so the coupling and solution procedures must handle arbitrary and exact models, with nonlinear and time-varying equations. Approximations are made in the components, and are indeed required for practical solution of most problems. Thus new technology and more accurate models are introduced by constructing new components, without changing the framework of the analysis.

The building-block approach itself leads to more general and more rigorous models. CAMRAD II has separate physical and logical pieces, and separate structural dynamic and aerodynamic models. Each piece must be capable of a general analysis. In CAMRAD/JA, the solution procedure mixes the part and loop solution for the rotor and airframe motion; and the iteration variables are not all identified. In CAMRAD II, the solution procedures have sound mathematical bases; and the iteration variables are automatically identified. In the wing models of analyses such as CAMRAD/JA, the aerodynamic geometry is assumed to be that of a specific structural model; and first-order approximations for the velocity and displacement at the collocations points are used. The wing model in CAMRAD II has general line geometry, so to the aerodynamic model droop and sweep are no different than flap, lag, and bending motion; and the wing can be connected to any structural model, with exact kinematics in the calculations of the velocity, displacement, and force at the collocation points.

Exact Kinematics

For all structural dynamic components, CAMRAD II implements exact kinematics of the rigid body motion and frame motion, and of the structural dynamic interfaces. Thus the analysis must handle large displacements, and the exact kinematics of large rotations. A structural dynamic component typically makes approximations in its model of elastic motion, but not in the kinematics of the rigid body motion, or the connections with other components.

The structural dynamic interfaces are illustrated in figure 4 (the positions are shown before the components are connected). A cantilever interface is a connection with no relative motion. It equates the linear and angular motion of points on two components; the constraint force can be in the connection axes or in the common frame axes. A pinned interface is a ball joint connection, which equates only the linear motion of points on two components. A torque interface is also implemented, which is a special (approximate) structural dynamic interface, connecting only rotational motion and torques. A torque interface can act only on the appropriate joints of a component. It produces no net moment on a true structural dynamic component, being involved only in the joint equations; so the load paths of the system will not be correctly modelled. The constraint equation for a cantilever interface is:

$$0 = B_l = \begin{pmatrix} r^{AB} \\ s^{AB} \end{pmatrix}$$

$r^{AB} = x^{AP/P} - x^{BP/P}$

s^{AB} = three variable representation of $C^{AB} = C^{AP} C^{PB}$

x = displacement of connection relative parent frame P, in P axes

C = rotation matrix from parent frame to connection axes

Considering exact kinematics in this manner is not difficult or expensive itself, but has the consequence that assembly of the system can not be implemented by simply identifying degrees of freedom or variables of two components as equal. Instead it is necessary to solve these nonlinear, time-varying constraint equations for some variables (degrees of freedom or forces).

Retaining exact kinematics is needed in order to model arbitrary configurations, undergoing arbitrary motion. In particular, it is essential for the capability to model general rotor hubs, since otherwise the rotating-to-nonrotating frame connection is special (since it involves large rotation). In analyses such as CAMRAD/JA, there is one rotating-to-nonrotating frame connection, at a hub node; and the control system is modelled by a pitch bearing with a spring/actuator. Most rotors have a fully rotating hub (the rotating-to-nonrotating connection is not at the hub node) and a control system including a swashplate (with one or more additional rotating-to-nonrotating connections). Even with a structural model for the pitch horn and pitch link, the control system load path model is wrong without a swashplate node. CAMRAD II can implement an arbitrary, general hub and swashplate model. Figure 5 illustrates the potential importance of the control system load path. For this tiltrotor operating in cruise, the total rotor thrust of 1300 lb is less than the total pitch link load of 1800 lb. So the hub axial shear force is only 500 lb, and in the opposite direction from what would be obtained ignoring the load path through the swashplate.

Motion Representation

A standard means to define the characteristics of system variables is required. These variables include the component degrees of freedom, frame motion, interface variables, input variables, and output variables. Many features are required in order to model a rotorcraft. Such sophistication is managed by implementing the model once, for use by the entire analysis. Specifically, the analysis must handle the following characteristics of the response of any system variable.

a) Motion representation.
b) Convergence test, perturbation, and mode normalization.
c) Order reduction (zero, dynamic, or quasistatic; for trim, transient, and flutter tasks).
d) Initialization.
e) Evaluation of response for a system with more than one period. For each component input variable, it is necessary to consider the period of the response required (determined by the current part solution) and the period of the response available (as calculated by another part).
f) Interpolation and derivatives, when evaluate response.
g) Filtering when evaluate response (mean, peak-to-peak, rms, harmonics, etc.).
h) Child response in trim.

Regarding the child response in trim, the system can have symmetries that in certain operating conditions imply a relation between the solutions for various subsystems. This relation can be enforced by defining the response of one subsystem as the child of another subsystem, such that they have identical motion except for a possible phase shift and/or sign changes. Then it is only necessary to solve for the parent response, which significantly reduces the computational effort. For example, this capability allows the solution for the motion of just one blade of a multi-bladed rotor. It is an option, since it is also necessary to be able to solve for the response of all subsystems, separately or together. For example, with a universal joint at the rotor hub, or with different or damaged blades, the rotor blades will not have identical motion.

The response of a variable is assumed to take the following form, introducing nominal and reference motion:

total = nominal + degree of freedom
= nominal + (reference + difference)

The nominal and reference can be different forms of motion; for example, the sum of the nominal and degree of freedom can involve the addition of axis motions. The reference can be updated from the solution for the difference (so the sum of the reference and difference must involve scalar addition). The solution procedure solves for the difference, which is the motion relative the prescribed nominal and reference. The nominal and reference should be chosen to help the solution process: to keep the difference reasonable small, or periodic; to avoid singularities in the representation of rotations; to introduce a specified operating condition. The nominal and reference keep the difference small by accounting for the rest position and any large rotations and displacements. The analysis does not assume that the difference is small, but many solution procedures work better if it is. The following conventions are implemented for the nominal and reference motion:

a) Rigid motion conventions: base frame, rotating frame, rest position.
b) Other motion conventions: turning frame, rotating variable, rest position, none.

The base frame convention uses a specified operating condition; it can be free (body or stability axes) or constrained.

The representation of rigid response is used for component rigid body motion and for frame motion. Scalar, three-parameter representations of the linear motion q and angular motion p are required. The motion of axes is described by the displacement and rotation relative parent axes: x, C, and their derivatives. The following options are implemented to represent the angular motion: aircraft Euler angles (Tait-Bryan); Rodrigues parameters (Euler-Rodrigues); arbitrary Euler angles. The following options are implemented to represent the angular motion (of axes B relative axes A):

inertial axes displacement: $q = x^{BA/A}$ = displacement measured in A axes

body axes displacement: $q = x^{BA/B}$ = displacement measured in B axes

body axes velocity: $\dot{q} = v^{BA/B}$ = velocity measured in B axes

These representations can be recognized in terms of the corresponding inertial acceleration:

inertial axes displacement:
$$\dot{v} + \omega \times v = C^{BA}\ddot{q}$$

body axes displacement:
$$\dot{v} + \omega \times v = \ddot{q} + 2\,\omega \times \dot{q} + \dot{\omega} \times q + \omega \times \omega \times q$$

body axes velocity:
$$\dot{v} + \omega \times v = \ddot{q} + \omega \times \dot{q}$$

With the body axes velocity representation, the displacement x is not obtained from q, but rather from the integral of the derivative of q. Hence

$$x^{BA/A} = \int C^{AB}\,\dot{q}\;\;d\,t$$

and the displacement x is path-dependent. In CAMRAD II, a complete evaluation of the displacement by this integral is not implemented. Instead, the analysis only uses the trim reference, plus a perturbation term for the flutter task. Hence the use of body axes velocity coordinates is only allowed for a frame whose parent is the inertial frame. Body axes velocity coordinates should not be used if displacement relative the inertial frame is important, such as for wake positions or ground effect.

In aircraft dynamics, it is conventional to represent the system rigid motion by body axes velocity coordinates. CAMRAD II can also use for the system rigid motion one of the other two representations; they are correct, but unconventional. The constraint equations for structural dynamic interfaces are best obtained from displacements at points on two components. This displacement is measured relative the common parent frame of the two components. Hence body axes velocity coordinates (giving path-dependent displacement) can not be involved in the motion of the two components relative their common parent frame.

Frames

Frames are used to help the derivation and analysis, by providing a description of the motion appropriate to the specific configuration and response. For example, the frame motion can be degrees of freedom (the frame equated to some rigid body motion); the component motion relative the frame can be small; or components can be coupled relative to their common frame (and the constraint equation only requires the motion relative that frame). Figure 6 illustrates component rigid body motion and frame motion (motion of axes). The component rigid body motion is measured relative to a frame. The frame definition can be hierarchical. The response is defined for each frame and for the component rigid motion. Hence the total response has the following form:

motion = frame + frame + ... + variable

frame = nominal + (reference + difference)
variable = nominal + (reference + difference)

The frame motion can be prescribed or degrees of freedom. Frame degrees of freedom are implemented by identifying the frame as the rigid body motion of a particular component. With this approach, the symmetry of the system equations is lost until the structural dynamic constraints have been eliminated. However symmetry is also lost with input/output interfaces; with the force of a cantilever interface in connection axes rather than in the common frame axes (typically used at a rotating-to-nonrotating connection); or with components that are not structural dynamic kind.

In the rotorcraft model of CAMRAD II, an airframe frame is used in order to follow the conventions of aircraft dynamics. Rotor and blade frames are used to help define the motion. The airframe frame has the inertial frame as its parent. It is attached to the airframe component rigid body motion (frame degrees of freedom). The airframe frame axes are the center-of-mass/mean axes of the airframe component; and the rotorcraft inertia is defined so they are usually the center-of-mass/mean axes of the system. The motion is represented by body axes velocity coordinates (or inertial axes displacement), and aircraft Euler angles. The airframe frame is the parent frame of the rest of the system: so the operating condition is only required for the airframe frame motion; so structural dynamic interfaces (relative their common frame) do not require position relative to inertial space; and so it is possible to use a body axes velocity representation of the system rigid motion. The CAMRAD II model also uses a rotor frame at the nonrotating hub node (frame degrees of freedom; parent is airframe frame); and blade frames (rotating; frame degrees of freedom; parent is rotor frame). Using frame degrees of freedom here is a choice; the rotor and blade frames could as well have prescribed motion (relative the airframe frame).

Regarding the system rigid motion for an aircraft, it is conventional to represent the motion by center-of-mass/mean axes (relative to which the entire system has zero linear and angular momenta). The problem is that these axes are not the motion of a physical point; and a transformation to mean axes is not implemented (for a linear system such a transformation can be obtained from the mass matrix, but the process is more complicated for a nonlinear, time-varying system). Therefore a component is used for which the rigid body axes are the mean axes of the component (obtained with linear normal modes for the elastic motion); and the system inertia is defined such that these are usually also the mean axes of the entire system. The system rigid motion in trim is defined by the operating condition. The problem is that it is complicated to use this operating condition to describe the trim motion of all components. Therefore the operating condition is used to describe the motion of the base frame (whose parent is the inertial frame), and all other motion is defined relative to that frame. It is conventional to represent the system rigid motion by body axes velocity coordinates. The problem is that it is then complicated to obtain the position relative to inertial space. Therefore body axes velocity coordinates are used to describe the motion of the base frame, and all other motion is defined relative to that frame. Then since coupling components requires only the motion relative their common frame, the position relative to inertial space is not required.

Free Degrees of Freedom

The system can have free degrees of freedom: motion with no elastic restraint, so the spring is zero or singular. It is not possible to solve the trim equations for the constant equilibrium position of such variables (or the mean of the periodic equilibrium position). Hence special treatment of free degrees of freedom is required in the trim solution procedures. It is necessary to extract the mean position for special treatment, without modifying the physical model. An arbitrary number of such variables must be handled. The free degrees of freedom typically include the six system rigid degrees of freedom. Other free degrees of freedom may be present however, such as drive train or sling load variables, even for a constrained system (wind tunnel configuration). Free degrees of freedom are associated with the operating condition. For each variable it is possible to specify a value of the mean position (second order variables), or of the mean position and velocity (first order variables).

Main Rotor and Tail Rotor Helicopter

For the main rotor and tail rotor configuration, there are two periods involved in the system behavior. Usually a system period exists: a period that is a common multiple of both the main rotor and tail rotor periods. However, this system period is too large for use in a practical trim solution. It is always possible to obtain the exact, fully coupled solution using the transient task. For the trim task, an approximate but practical solution is required when several periods are present. The approach is to solve for the response at each period separately, ignoring the non-harmonic vibratory coupling between parts. A rotor is a periodic part: it inherently involves a particular period. A periodic part can be solved only for the response at that period. The assumption of periodicity requires that any input from other parts be at that period, or else only the mean value can be used. The airframe is a time-invariant part: it has no inherent period. A time-invariant part can be solved for the response to input at all periods. The response is solved separately at each period, which is an approximation if the part equations are nonlinear. The analysis must automatically handle evaluation of the response for a system with more than one period. For each component input variable, it is necessary to consider the period of the response required (determined by the current part solution) and the period of the response available (as calculated by another part). For the flutter task, it must be possible to average a subsystem (rotor) over its own primary period. Thus for both the trim and flutter solutions, the capability to partition the system is required. Specifically, it must be possible to separately solve for the main rotor, tail rotor, and airframe motion; and iterate between them until a converged solution is obtained.

Transportability

CAMRAD II was not developed for a single organization, so it must be easily installed on many different computers. For transportability, CAMRAD II is written in standard Fortran. The programming language of engineering remains Fortran, which is generally satisfactory for the mathematical calculations required in aeromechanics. Also, the customers of CAMRAD II are aeronautical and mechanical engineers, not software engineers; hence the choice of Fortran rather than C.

Fortran does not however have the data structures needed to implement a flexible analysis. The building-block approach means the analysis can have an arbitrary number of pieces of each class and type, with arbitrary sizes. Fortran offers common blocks and subroutine arguments as means to transfer data between modules. In general more complicated data structures and the means to access them are needed. Some specific requirements are as follows.

a) The data structures required (ordered sets of real/integer/character variables and arrays) include records and list records as well as commons.
b) Access to only selected variables in a data structure is needed, and the capability to reference variables by local names.
c) Implementing changes (including dimensions) to the contents of a data structure must not require modifying the code.
d) Data structure information must be obtained from a single location (a dictionary), for both coding and documentation.
e) The input and output of subroutines must be clearly visible.
f) Variable array dimensions in the dictionary and code are

needed, with numerical values of the dimensions in the dictionary.

Thus CAMRAD II is written using a software tool. This software tool was designed for the development, modification, and maintenance of large Fortran programs. It emphasizes the definition, access, and documentation of data structures.

The software tool is a combination of a dictionary and a translator. The dictionary is the sole location for information about data structures (form, contents, and documentation). The code is written with a prologue that defines subroutine communication (input and output) through data structures; and information for documentation of the subroutine. Variables in records and lists are used almost like standard Fortran variables. The translator produces compilable Fortran source from code written using various constructions, and the dictionary information.

Ease of Use and Productivity

A comprehensive analysis must be easy to use, especially for normal or typical configurations. This is not the same as saying that helicopters will be easy to analyze. A flexible analysis (the CAMRAD II core system) requires a large amount of detailed input information. A helicopter is a complex system, requiring thousands of system pieces to produce a model, especially with aerodynamics involved. It must be expected that modelling unique configurations will require considerable effort. However, it must be possible to model typical helicopters with no more effort than required by analyzes such as CAMRAD/JA. Thus CAMRAD II has a rotorcraft shell that constructs the core input for typical configurations and typical problems. Figure 7 shows several models built using the shell. The rotorcraft shell constructs an aircraft with one or two rotors; in free flight or in a wind tunnel; and an N-bladed rotor, with an articulated, hingeless, teetering, gimballed, or bearingless hub; perhaps with a swashplate.

Figure 8 summarizes the CAMRAD II input process. The shell isolates the user from the details of the system definition at the core level. The shell creates the components and other system pieces, from parametric input and from assumptions about the system configuration and model. Built-in values for all parameters significantly reduce the amount of input required. In initialization, all parameters are set to default values, before the input is read. In a scenario, selected parameters are given values after reading the input (perhaps calculated from the input). For example, the rotorcraft shell has elementary scenarios for simplified configurations; and has scenarios for forward flight and hover wake models. The shell accomplishes a 2 or 3 order-of-magnitude reduction in the amount of input information required. The shell input of course does not have the flexibility of the core input, and may not be able to model exactly the configuration being investigated. Even in such cases, the shell constructs most of the system, minimizing the need to deal directly with the core input, and providing guidance for the use of core input. It is always possible to use core input to change the model constructed by the shell.

Productive use of a comprehensive analysis requires a reasonable computer execution time. Figure 9 summarizes the experience with CAMRAD II. Both cpu time and the product of cpu time and hardware cost are shown, over four generations of computers. On the ordinate, 1.0 represents a job with a long but acceptable execution time. The original development of CAMRAD II included what was necessary to bring CAMRAD II execution times (on current hardware) below CAMRAD/JA times (on late 1980's hardware). The faster hardware more than compensates for the slower software.

CAMRAD II execution time depends primarily on model complexity. A hierarchy of models is available to best balance efficiency and accuracy. It is important to use the simplest model that will perform the required analysis. It is also possible to reduce the complexity of the system by constructing components that do more internally, including internal interfaces and specific assumptions about the configuration. With this approach computation time can be reduced, but the components become more complicated and the analysis is much less flexible. As an example, a rigid wing component has been implemented, combining a lifting-line wing with a rigid body structural model.

CAMRAD II development is resource-limited. For future development it will be necessary to choose between faster execution; improved convergence; or advanced technology. For execution time, the basic choice is whether to rely on hardware advances, or to develop faster software, perhaps by constructing rotor blade or rotor components. If the next generation of workstations give another factor of five in hardware speed, there will be little incentive to develop faster software.

Demonstrated Capability

A major objective of CAMRAD II applications has been to demonstrate the capability and maturity of the analysis. The approach involves demonstrating the capability to handle basic rotorcraft behavior; re-examining CAMRAD/JA correlations; and considering cases beyond the capabilities of CAMRAD/JA. Table 3 summarizes the applications.

There is certain basic behavior of rotorcraft that a comprehensive analysis must be able to handle. In some cases this basic behavior is even known quantitatively. In a complex code, most things must be working correctly just to do simple problems. A number of the CAMRAD II applications were intended to demonstrate the capability to handle basic rotorcraft behavior.

In a correlation project, most time is spent getting the input data and experimental results; actually running the code is a small part of the work. A helicopter is a complicated system, so a large amount of information is required to describe it in the detail needed for a comprehensive analysis. Acquiring and checking that information can take several months. Obtaining the experimental data, and the information needed to assess and understand it, also takes much effort, and is best done with the help of the persons who conducted the test. To minimize the effort needed to deal with the input data and experimental results, the present work was restricted primarily to cases that had been seen before. Thus CAMRAD/JA correlation was re-examined. CAMRAD II input data were obtained from CAMRAD/JA input, and the experimental results were generally already available. It was also possible to compare CAMRAD II results with CAMRAD/JA, as well as with experiment. In particular, this helped establish what to expect from the CAMRAD II correlation. Finally, with this approach CAMRAD II inherits all the experience with CAMRAD/JA.

Most CAMRAD/JA cases required significant approximation to fit the real helicopter to the CAMRAD/JA model. With CAMRAD II significant improvements in the model were easily introduced. For example, several of the rotors analyzed have swept tips or elastic control systems. In CAMRAD/JA the blade elastic axis must be straight, and the control system is represented by motion at the pitch bearing. CAMRAD II can construct a blade with a swept tip, and can construct a swashplate model. CAMRAD II can also analyze rotors that CAMRAD/JA can not handle at all, in particular bearingless rotors.

Table 3 summarizes the rotors analyzed. In addition, an oscillating wing was analyzed. The following notes describe the columns in the table.

a) System: "mr" = main rotor; "tr" = tail rotor.
b) Airframe configuration: "WT" = wind tunnel; "hel" = helicopter.
c) Airframe transmission: "a" = asymmetric, "s" = symmetric; "1 rtr" = one rotor; "g" = governor.
d) Rotor: N = number of blades; R = blade radius (ft except for SA349); σ = solidity ratio.
e) Rotor rotate: direction of rotation ("cc" = counter-clockwise; "c" = clockwise).
f) Rotor SP: swashplate model; "P lock" = prescribed collective and cyclic control at pitch bearing; blank means pitch bearing with prescribed control and spring for control system flexibility; "SP+PL" = swashplate and pitch link model.
g) Blade hinges: "F" = flap, "L" = lag, "P" = pitch (hinges listed in order from hub); "U" = flap-lag or lag-flap universal joint; "G(FL)" = elastomeric flap-lag joint (gimbal); "T" = teetering hinge on 2-bladed rotor; rotors with just pitch bearing are hingeless; "B+S" = bearingless rotor, with snubber; "G+P" = gimballed hub for XV-15.
h) Blade element: number of rigid and elastic elements in blade model (each hinge requires a node, and hence there are short elements at the root; these short elements are usually modelled as rigid); "rigid" means all rigid elements, and last element is a rigid wing component; "3R+4E" means three rigid elements (for hinges at the root) plus four elastic elements (including one for swept elastic axis of tip).
i) Aerodynamics: number of aerodynamic panels on blade, and blade tip characteristics.

Concluding Remarks

CAMRAD II is an aeromechanical analysis of helicopters and rotorcraft that incorporates a combination of advanced technology, including multibody dynamics, nonlinear finite elements, structural dynamics, and rotorcraft aerodynamics. CAMRAD II uses a building-block approach to achieve flexibility in the model of the dynamic and aerodynamic configuration. Hence it can model the true geometry of a rotorcraft, including multiple load paths. CAMRAD II provides a powerful analysis capability, including advanced rotor aerodynamics; rigorous kinematics and dynamics (with consistent structural loads and dynamic response, and general interfaces between aerodynamic and structural dynamic components); and general transient solutions. For ease of use a shell is provided to build typical rotorcraft and rotor models, while the core input capability always gives complete flexibility to define and revise the model. A range of components and modeling options makes it a practical engineering tool, allowing the best balance of efficiency and accuracy to be found for a particular problem. CAMRAD II offers a common tool among organizations, and a design for growth that makes it an appropriate platform for future developments, for continuing access to new technology.

ENVIRONMENTAL	PHYSICAL	LOGICAL
case	component	loop
wind	frame	part
operating condition	interface	transform
period	output	modes
	input	response

Table 1. CAMRAD II system pieces.

rigid body	lifting line wing
normal modes	
beam	wing inflow
rod/cable	rotor inflow
transmission	wing wake
reference frame	
	wing wake geometry
filter	rotor wake geometry
reference plane	
	wing performance
differential equation	rotor performance
programmable	rotorcraft performance
transfer function	
	rigid wing
Fourier series	
prescribed control	helicopter tail boom
gust	
rigid airframe aerodynamics	
airframe flow field	

Table 2. CAMRAD II components (Release 1.1).

System		Airframe		Rotor					Blade		Aerodynamics	
		config	trans	N	R	σ	rotate	SP	hinges	element	panel	tip
elementary		WT		4	20.	.075	cc	P lock	FP	rigid	20	
LV		WT		2	3.43	.0464	cc	P lock	T+P	rigid	15	rect
						.0396						ogee
lateral flap		WT		4	2.73	.0891	cc	P lock	FLP	rigid	20	
AH-64	mr	hel / WT		4	24.	.092	cc	SP+PL	FPL	3R 4E	25	20° at .95
	tr			4	4.58	.2256	cc	P lock	FP	rigid	9	
H-34	mr	hel / WT		4	28.	.0622	cc		U(LF)P	2R 3E	19	
	tr			4	4.67	.167	cc	P lock	FLP	rigid	8	
SA349		1 rotor		3	5.25 m	.06366	c	SP+PL	FPL	3R 4E	15	
Puma		WT		4	24.724	.091	c	SP+PL	U(FL)P	2R 4E	19	BERP type
CH-46		tandem		3	25.	.0573	c/cc	P lock	FPL	rigid	20	
OH-6	mr	helicopter	a + g	4	13.167	.0544	cc	P lock	FLP	rigid	20	
	tr			3	2.125	.1198	cc	P lock	FLP	rigid	8	
S-76		WT	1 rtr	4	22.	.07476	cc	SP+PL	G(FL)P	2R 4E	15	30° at .95 taper
ITR C		WT		3	2.661	.0494	cc	P lock	U(LF)P	rigid	15	
Mod2 WT		WT		2	150.	.03	cc	P lock	T+P	1R 3E	17	blade taper
ITR A		WT		2	3.156	.0572	cc		P	2R 3E	20	
ABC		coaxial		3	18.	.0635	cc/c	P lock	P	1R 3E	17	blade taper
Bo-105		WT		4	16.11	.07	cc		P	7E	20	
ITR D		WT		2	2.96	.0242	cc	SP+PL	B+S	2R 3E 1R 1E	15	
XV-15		WT	1 rtr	3	12.5	.089	cc	SP+PL	G+P	4E	15	
XV-15		tiltrotor	s + g	3	12.5	.089	cc/c	SP+PL	G+P	4E	15	

Table 3. CAMRAD II applications.

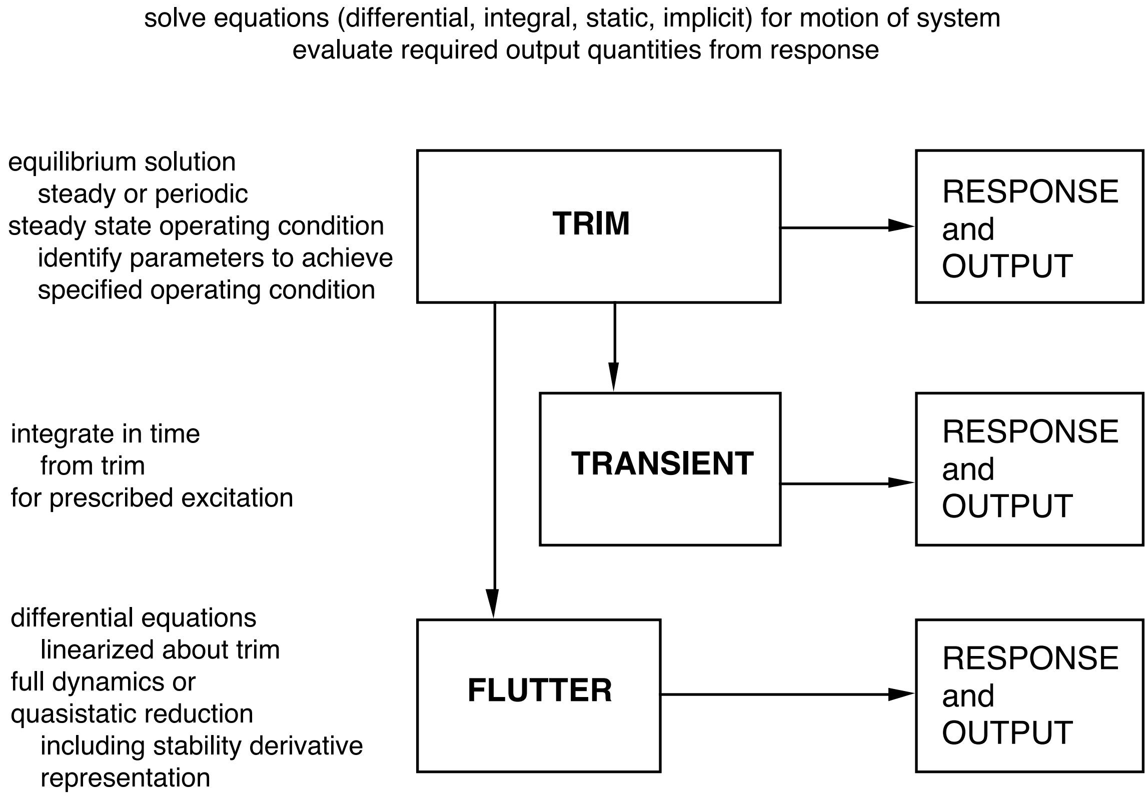


Figure 1. CAMRAD II tasks.

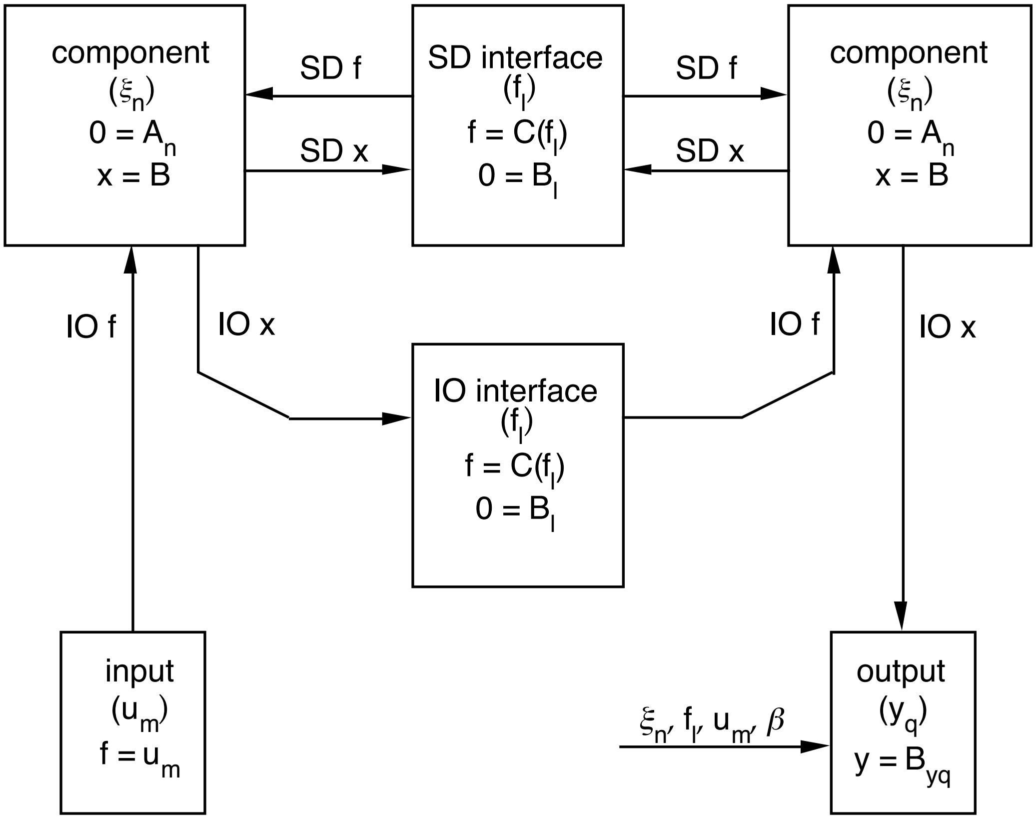


Figure 2. System equations.

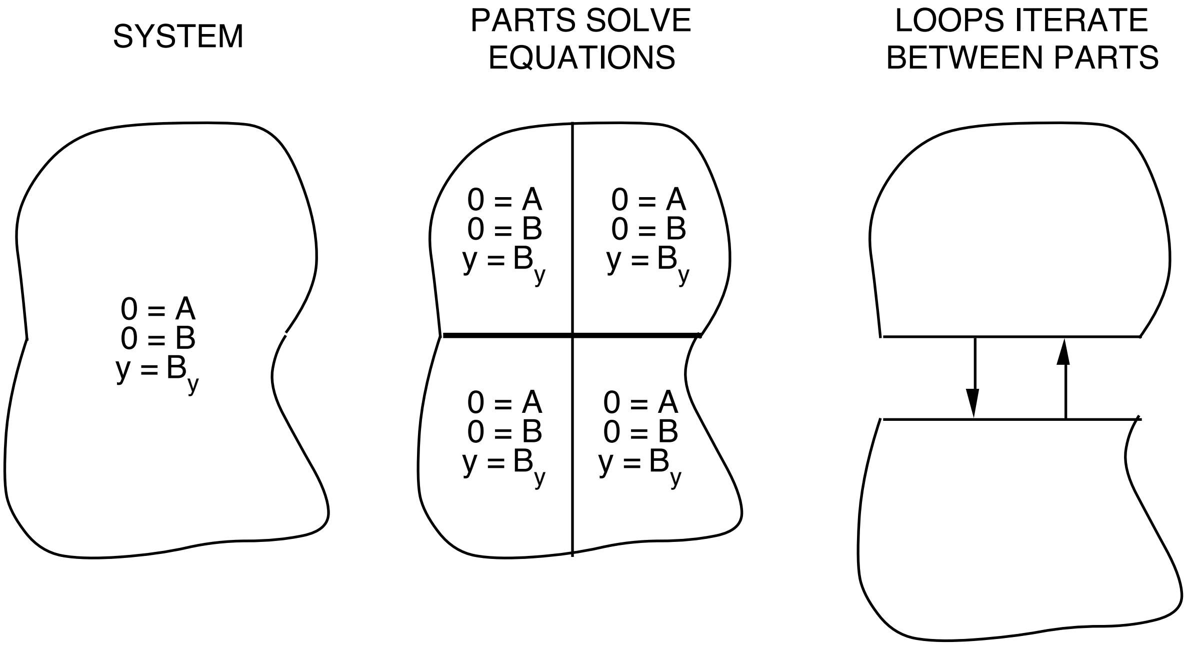
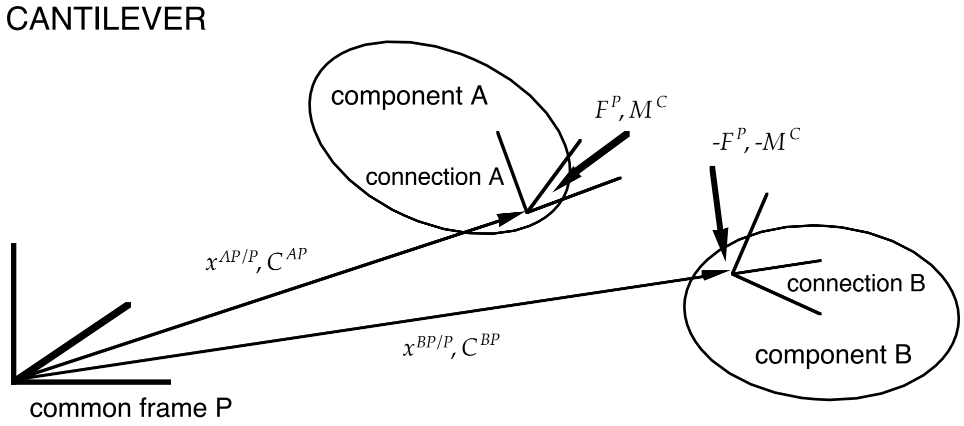


Figure 3. System solution procedure.



equate linear and angular motion
$x^{AP/P} = x^{BP/P}, C^{AP} = C^{BP}$
(connection axes C = A = B)
(constraint force can be in connection axes, F^C not F^P)

Figure 4. Structural dynamic interfaces.

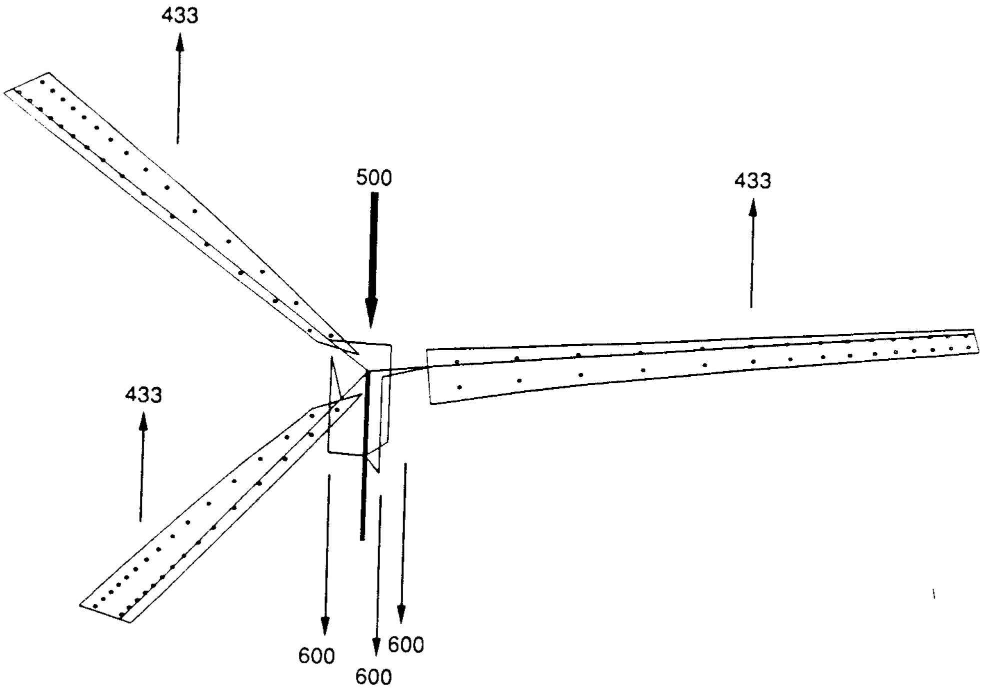


Figure 5. Influence of control system load path on rotor forces.

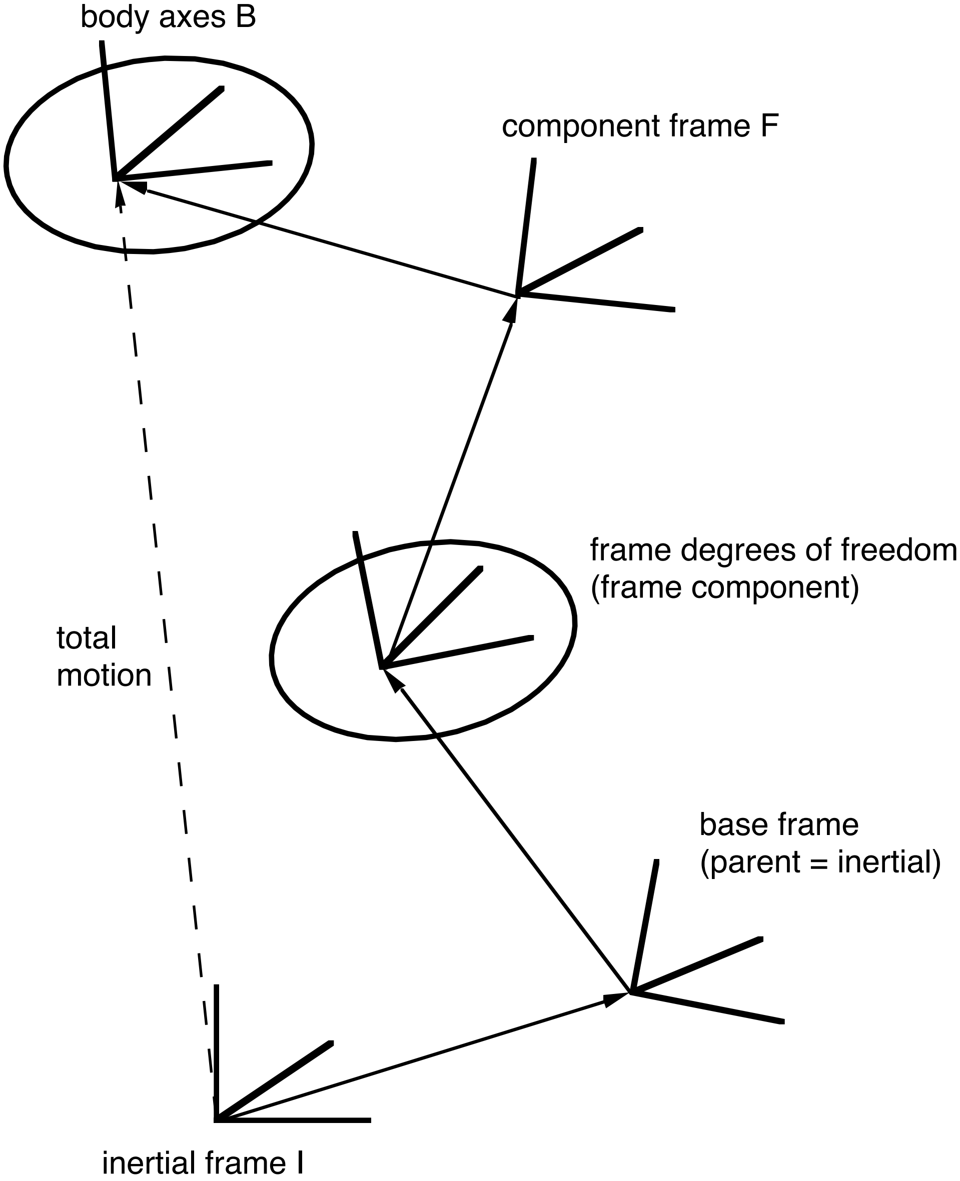


Figure 6. Component rigid body motion and frames.

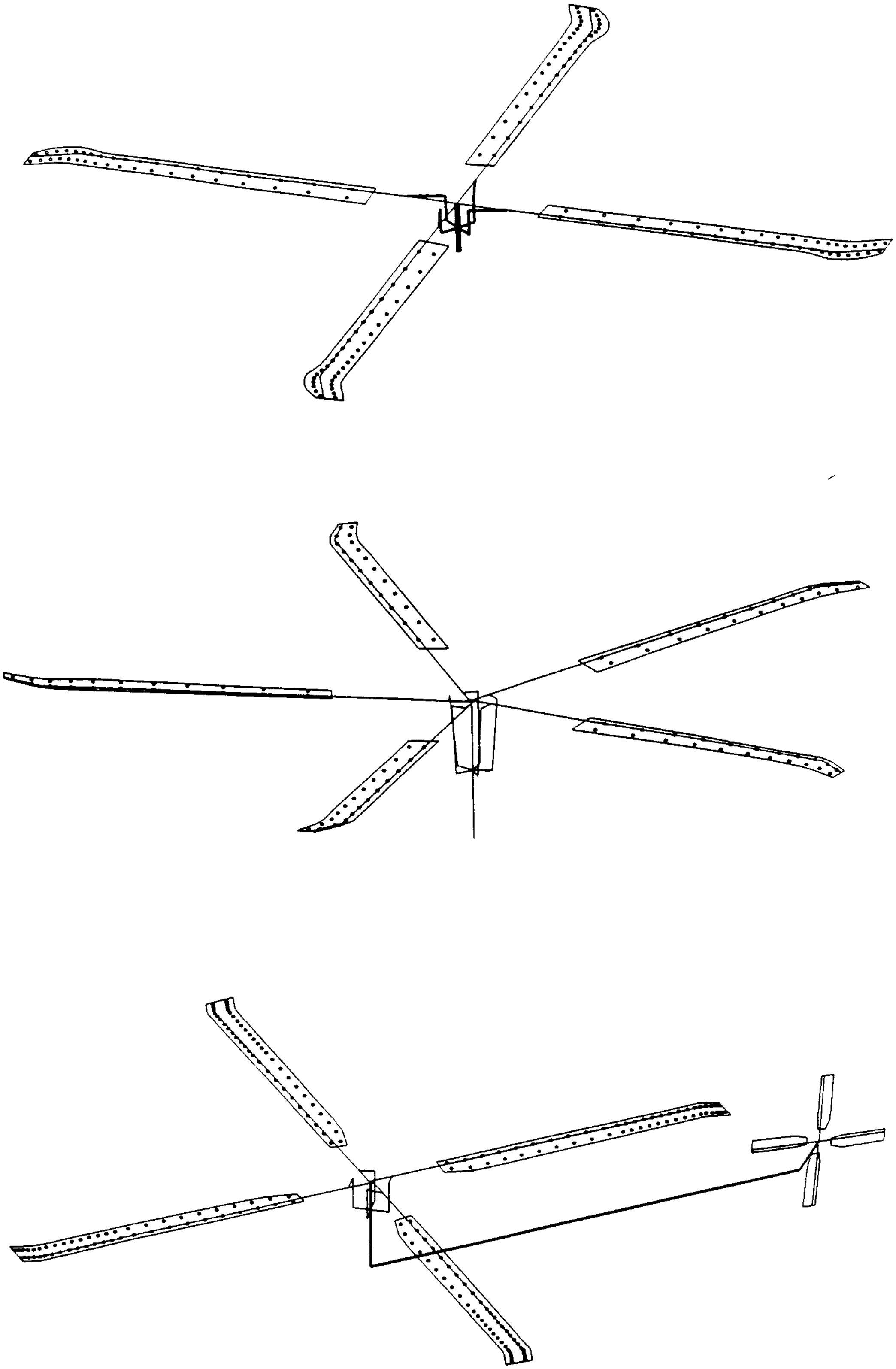


Figure 7. CAMRAD II models of articulated rotor, bearingless rotor, and helicopter.

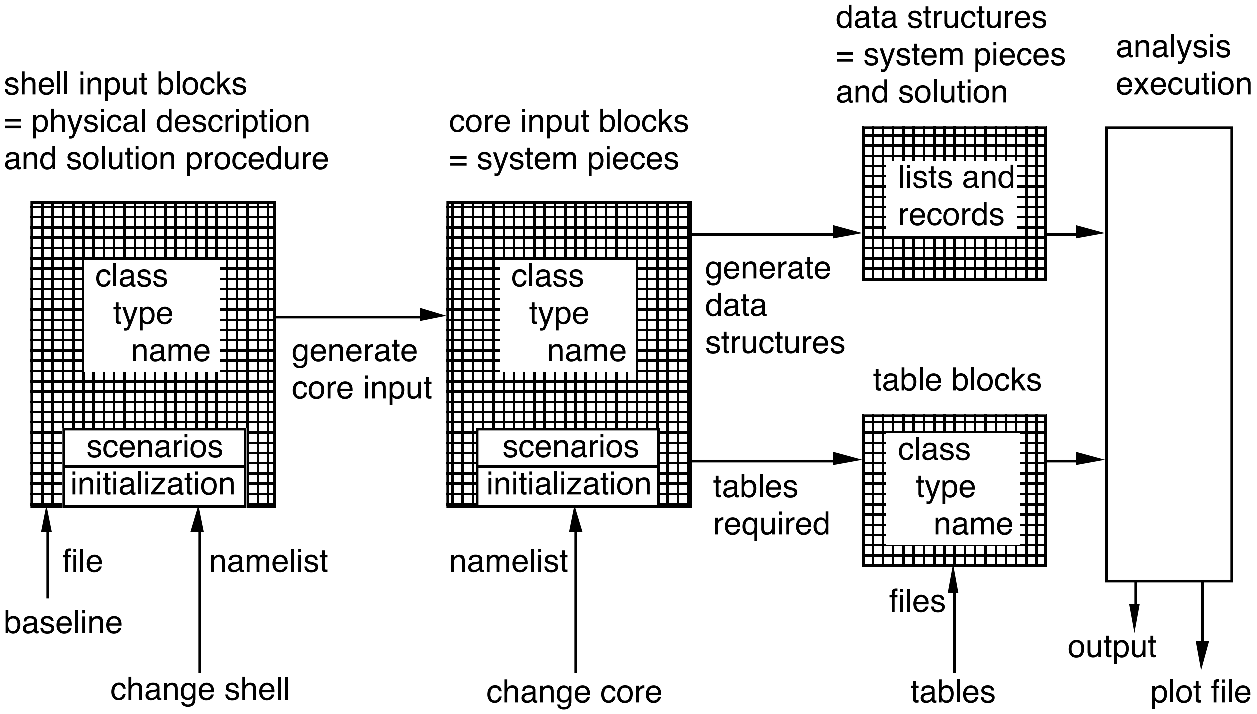


Figure 8. Summary of input process.

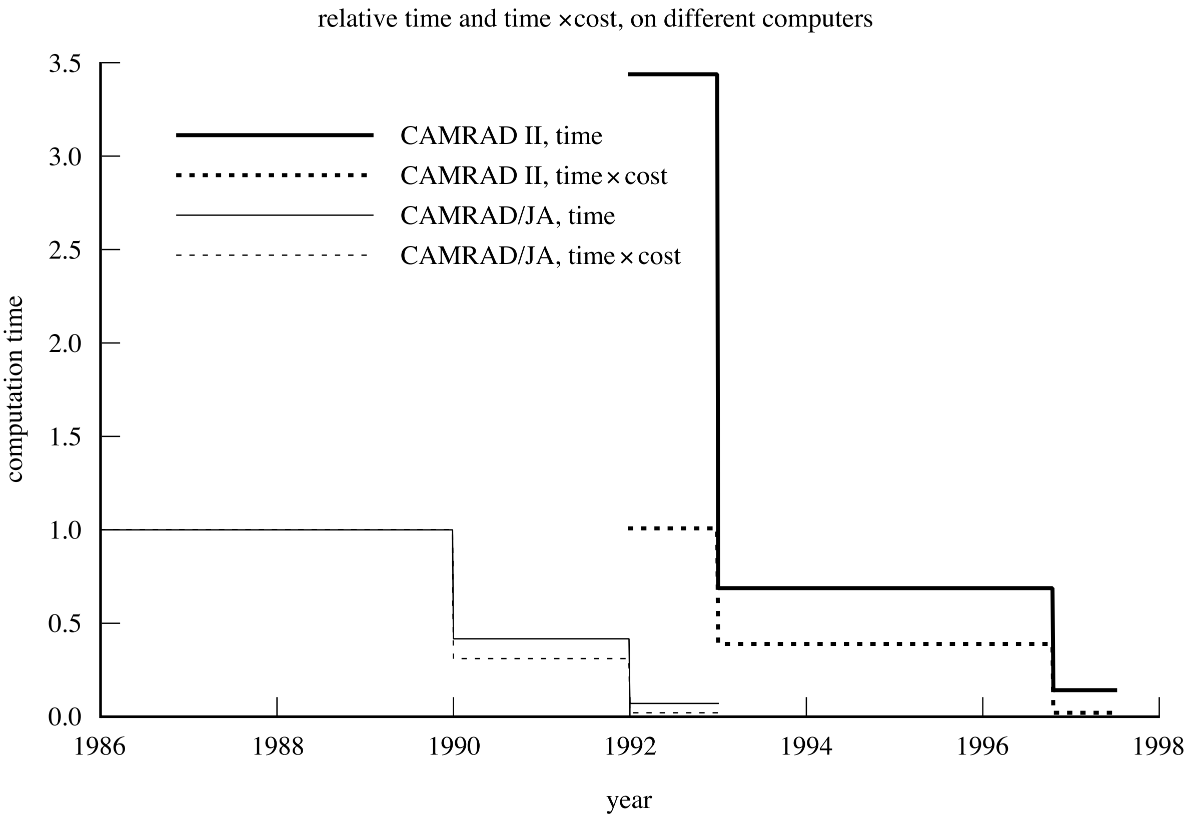


Figure 9. Comprehensive analysis productivity.