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# Robust trim procedure for rotorcraft configurations

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ABSTRACT

This paper presents a highly robust trim procedure for a generic rotorcraft configuration. The procedure acts externally on time marching models to produce a trim solution and is applicable over a wide range of rotorcraft configurations, including conventional helicopters, coaxial rotor systems, tandem, and side-by-side configurations. Examples for each of these configurations are provided. It successfully determines a trim solution regardless of model non-linearities, number of modeling states involved, model contents, numerical methodology, or the stability characteristics of the configuration under discussion, without exploiting any additional stabilization mechanism. The method is shown to be highly robust and insensitive to the initial guess for the trim variables, which substantially simplifies the trim process although at a certain expense in computational time.



## 1. Introduction

Despite tremendous advances in computational capability and algorithm sophistication, trimming a detailed rotorcraft model remains a complex challenge. Obtaining a trim state is a fundamental requirement for measuring performance, efficiency, and vibrational characteristics of any rotorcraft configuration. Rotorcraft simulators also require trim solutions as an initial condition for a simulation and validation of any maneuvers.

For a given rotorcraft model and a set of flight conditions, a typical trim procedure provides a set of rotorcraft trim variables (pilot commands, fuselage attitude angles, etc.), as well as other rotorcraft states (flapping angles, elastic deflections, downwash states, etc.), which are all a result of the above trim variables, and ensure a trimmed flight (at least instantaneously). Several methods exist today for the formulation and solution of a generic rotorcraft trim problem, including:

1. "Force-Moment Balance" [1,2]: all Degrees Of Freedom (DOF), such as body, blade flapping, elastic modes, etc. are approximated as analytical or numerical equations, which are solved iteratively using numerical methods (e.g. Jacobi, Gauss–Seidel, Newton–Raphson, etc.).
2. "Harmonic Balance" [3]: every DOF is expressed as a sum of harmonic signals of the main rotor rotational frequency, forming a set of $N_s(2N_h+1)$ equations, where $N_s$ is the number of model states and $N_h$ is the number of considered harmonics to be balanced. The solution is found iteratively by setting the fuselage DOFs' constant (mean) harmonics to zero.
3. "Periodic Shooting" [4,5]: searching for initial conditions that ensure all states will be identical at $\psi = 0$ and $\psi = 2\pi$. For any given set of initial condition, the equations are integrated along one rotor revolution. The errors between the state vector at the beginning and end of this revolution are minimized using a nonlinear solver.
4. "Autopilot Trim" [6,7]: attempting to "fly the helicopter to trim" using an initial guess. A control system drives the rotorcraft model until it stabilizes at the desired trim state. This requires a fairly robust autopilot, tailored to the analyzed configuration. Since autopilots are rarely available in the initial design stage (or at all), this method is only suitable for mature enough configurations and simulation software.
5. "Time Marching Trim" [6,8]: starting from initial guess, the model is time marched until all transients have decayed. A dedicated solver applies a set of "virtual springs and dampers" that would bring the errors in the constraints to zero.

Examining these methods reveals some deficiencies including sensitivity to initial guess [9–11], poor convergence characteristics, and the need to tailor the trim method to the model configuration, complexity, and number of states (number or rotors, blades, dissimilar blades, wake models, etc.). This stems from the trim

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**Nomenclature**

| | |
|---|---|
| $\{\bar{c}\}$ | Generalized trim variables vector ($=\{c_1 \dots c_6\}^T$) |
| $p, q, r$ | Fuselage angular velocity components in its (body) system |
| $u, v, w$ | Fuselage linear velocity components in its (body) system |
| $x, y, z$ | Cartesian coordinates |
| $()^{FR}$ | Main/Forward/Upper/Right Rotor, for a Conventional/Tandem/Coaxial/Side-By-Side configurations, respectively |
| $()^{AR}$ | Tail/Aft/Lower/Left Rotor, for a Conventional/Tandem/Coaxial/Side-By-Side configurations, respectively |
| $()^0$ | Time average component |
| $()^P$ | Periodic component |
| $()_F, ()_I$ | Fuselage and Inertial system related quantities, respectively |
| $\psi_F, \theta_F, \varphi_F$ | Fuselage Euler angles (heading, pitch, roll, respectively) |
| $\theta_0, \theta_{1c}, \theta_{1s}$ | Collective, Lateral and Longitudinal cyclic commands, respectively |

methods being inherently non-linear [9–11] and convoluted within the rotorcraft model. This work introduces a new and highly robust trim method for various rotorcraft configurations, designed to work externally with any time domain model, as it only requires a time history of the 6 mean body accelerations.

Fixed wing aircraft do not typically have oscillatory forces stemming from rotating blades. Therefore, fixed wing trim methods are typically less involved and do not suffer from the shortcomings described above. Although the current method was mainly designed for rotorcraft trim, it is also suitable for fixed wing trim problems without any necessary adjustments, as the fundamental elements of the method remain the same. Most fixed wing configurations typically have weaker coupling between input variables and output accelerations, which may also result in less restrictions on this method's algorithmic parameters, leading to even faster convergence.

## 2. A generic time-history solution

We shall first describe the main components of a generic rotorcraft system time-history response. The essential fundamental modeling components depend on at least two systems of coordinates – an Inertial System (I-system), and a Fuselage (body) System (F-system). The Inertial system is a reference stationary system relative to which all velocity and acceleration components are calculated. Unit vectors along the coordinate lines of this system have a fixed and arbitrary orientation: $\hat{x}_I \equiv$ North, $\hat{y}_I \equiv$ West and $\hat{z}_I \equiv$ upwards (opposite to the gravity acceleration direction).

The Fuselage system is attached to the airframe, typically at the center of gravity while its directions coincide with the body principal axes of inertia. In this work, unit vectors along the coordinate lines of this system are $\hat{x}_F$ directed towards the rotorcraft nose, $\hat{z}_F$ is oriented upwards, and $\hat{y}_F$ is directed towards the left hand side of the airframe. The Fuselage system directions may be obtained by rotating the Inertial system by the three Euler's angles $\{\psi_F, \theta_F, \varphi_F\}$ (heading, pitch, and roll angles, in this order).

Although trim is defined as a "steady flight", the response of a typical rotorcraft configuration is always periodic. Hence, each time-dependent function $f(t)$, may be written as $f(t) = f^0 + f^P$ where $f^0$ (the "DC" part) is the time average (mean) component and $f^P$ (the "AC" part) is the periodic part, the integral of which along a typical time-period (one rotor revolution) vanishes. Vector transformation between the F-system and the I-system is conventionally defined as

$$\{\bar{x}_F\} = \left[T^{FI}\right]\{\bar{x}_I\}, \tag{1}$$

where $\{\bar{x}_F\} = \{\hat{x}_F, \hat{y}_F, \hat{z}_F\}^T$, $\{\bar{x}_I\} = \{\hat{x}_I, \hat{y}_I, \hat{z}_I\}^T$ and the elements of the above $[T^{FI}]$ transformation matrix are founded on the average Euler angles. Linear and angular velocities in the Fuselage system will be denoted $\{u, v, w\}$ and $\{p, q, r\}$, respectively.

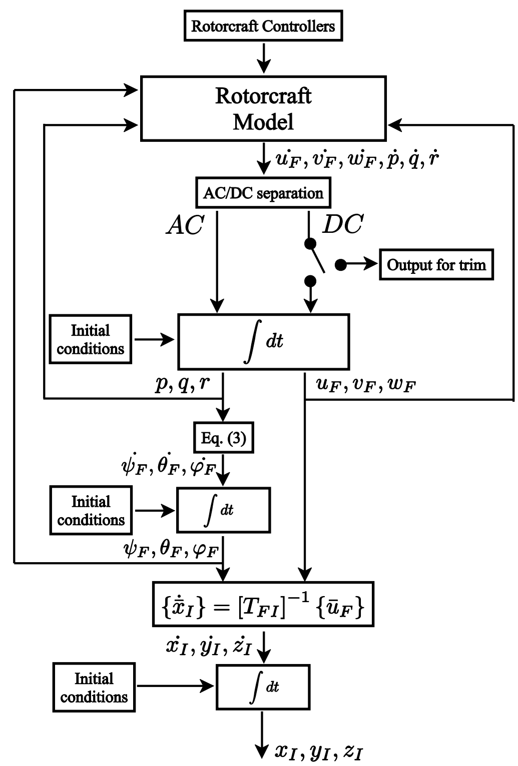


**Fig. 1.** Generic time marching scheme of a rotorcraft configuration.

This method makes use of a generic time marching integrator, and we concentrate on the required time marching operation mode to obtain a trim solution. The examples in this paper were generated by a detailed non-linear rotorcraft model, featuring a rigid airframe with aerodynamics tables for forces and moments, rigid blades with Mach and Reynolds tabulated airfoil characteristics (which includes stall modeling), and both uniform and full free-wake inflow models (additional details may be found in the work by Friedman et al. [12]). These modeling techniques results in a generally non-linear model for helicopter simulations.

Fig. 1 presents the schematics of a general time marching rotorcraft model, that includes all equations and modules required for modeling the rotorcraft performance. The trim method only requires the model to output the three linear and three angular accelerations as functions of time. The integration and coordinate transformation blocks exploit these accelerations to provide the model with the necessary velocities, angular rates, and Euler attitude angles. In simulating flight, the controller commands are assumed to be given either by a pilot or by an outside control