

AN EFFICIENT HELICOPTER MAIN ROTOR TRIM METHOD BASED ON COMPUTATIONAL FLUID DYNAMICS

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Abstract

This paper introduces a multi-dimensional “delta trim method” for computational fluid dynamics (CFD) simulations to compute the blade control settings that are essential for predicting rotor aerodynamics. The present trim method is based on the standard “delta trim method”, but it achieves higher computational efficiency by using a combination of multi-level grid spatial and temporal resolutions. Two representative benchmark results are presented, including the AH-1/OLS rotor in forward flight and the HART-II rotor in descent flight. The numerical activities demonstrated the effectiveness of the new trim method. In addition, the novel method saves approximately 12% and 31% CPU time in the AH-1/OLS rotor and HART-II rotor cases, respectively, compared to the standard “delta trim method”.

1. NOTATION¹

Symbols

a	Lift-curve slope, $a=5.7$
C_D, C_L, C_M	Drag, lift, moment coefficient
C_{Mx}, C_{My}	Rolling, Pitching moment coefficient
$C_n M^2$	Mach-scaled, normal force coefficient
C_T	Thrust coefficient
c	Chord length, m
k_x, k_y	Inflow coefficients
N_b	Number of blade
M_x, M_y	Rolling, pitching moment, N·m
M_T	Blade tip Mach number
R, R_c	Rotor, rotor cut-off radius, m
T	Thrust, N
U_P, U_T	Inflow velocity in perpendicular, tangential direction, m/s

α_s	Rotor shaft angle, deg
β	Flap angle, deg
δ	Lead-lag angle, deg
ε	Convergence threshold
φ	Azimuth angle, deg
λ	Inflow ratio
λ_c, λ_i	Climbing, induced inflow ratio
μ	Advance ratio
θ	Pitch angle, deg
θ_0	Collective pitch angle, deg
θ_{1c}, θ_{1s}	Lateral, longitudinal cyclic pitch angle, deg
θ_{tw}	Blade twist angle, deg
ρ	Density, kg/m ³
σ	Rotor solidity
Ω	Main rotor speed of rotation, rad/s

Acronyms:

BET	Blade Element Theory
BVI	Blade-Vortex Interaction
CFD	Computational Fluid Dynamics
DNW	German-Dutch Wind Tunnel
GCG	Generalized Conjugate Gradient
HART-II	Second Higher Harmonic Control Acoustic Rotor Test
MUSCL	Monotone Upstream-centered Schemes for Conservation Laws
RANS	Reynolds-Averaged Navier Stokes
ROSITA	Rotorcraft Software ITALy
SA	Spalart-Allmaras

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2. INTRODUCTION

Over the last three decades, the application of computational fluid dynamics (CFD) technology in helicopter rotor aerodynamics prediction has progressed tremendously. In numerical simulation of helicopter rotor forward flight cases, the determination of helicopter rotor trim state is important since the nature of asymmetrical air-loads of the main rotor leads to undesired moments with respect to the rotor hub. However, the simulation with the rotor control settings obtained from wind-tunnel tests always lead to an incompletely trimmed state. For this reason, it is necessary to employ a trimming process to improve the accuracy of helicopter rotor aerodynamics prediction.

The trimming process typically follows an iterative manner, where the trim variables (collective and cyclic pitch angles) are commonly solved using the Newton-Raphson iteration method (Ref. 1). The core elements of this procedure are twofold: estimating the initial trim variables and updating the trim variables. Both steps have a direct impact on the convergence speed and the computing efficiency of the trim calculation.

There are two different ways to obtain initial guesses of the trim variables in CFD simulations: wind-tunnel data (Refs. 2, 3) and estimates from blade element theory (BET) (Refs. 4, 5, 6, 7). Wind-tunnel data is often used, but it may not be available for cases where no experiments have been performed. BET is an efficient approach to obtain initial values, but it can lead to a slow convergence of the trimming iteration due to the inaccuracy of the initial trim data. To alleviate this issue, Ref. 6 uses an artificial neural network model to predict the aerodynamic coefficients in BET, which can provide more accurate initial guesses. However, the BET approach may not be ideal when considering the blade-vortex interaction (BVI) phenomenon.

For updating trim variables, two main categories are usually adopted, namely the direct method (Refs. 2, 3, 5, 7) and the “delta method” (Refs. 4, 8). The direct method uses only the CFD results to renew the trim variables during the iterative process, including the construction of the Jacobian matrix containing the sensitivity derivatives of the thrust and moment coefficients with respect to the trim variables. Although the trim results are accurate, the direct method is much computationally expensive because it requires running the CFD solver for at least four

rotor revolutions per trim cycle. In contrast, the “delta method” offers a more efficient way. It uses a simple aerodynamic model, such as the BET, to calculate the sensitivity derivatives, and then loosely couples the CFD solver and the simple aerodynamic model to update the trim data. This means that the CFD solver only need to be run once per trim cycle, which greatly improves the computing efficiency of trim calculation. Table 1 compares the number of rotor revolutions required to run in the CFD solver for the AH-1G main rotor trimming when using the direct and delta methods to compute the trim variables. The workload for the “delta method” is 70% lower than that of the direct method, which demonstrates its higher efficiency.

Table 1: Comparison of rotor revolution costs in CFD solver for different trim methods (Ref. 4).

Characteristic	Direct	Delta
Aerodynamic model	CFD	BET (Dress)
CFD revolutions	20	6
Workload ratio to direct method	1.00	0.30 (-70%)

In this work, the standard “delta method” is still introduced to construct a high-efficiency trim framework for helicopter rotor CFD simulation. Different from the trim approach adopted in Ref. 4, a novel routine that balances accuracy and efficiency is proposed to compute the trimmed data, in which a combination of multiple levels of grid and temporal resolutions is adopted to accelerate the trimming process, resulting the multi-dimensional “delta trim method”. The benchmark case studies are conducted to assess the effectiveness of this improved “delta trim method”. The computational efficiency of the developed method is reported for the sake of comparison with standard “delta trim method”.

This paper is structured as follows. Firstly, an overview of the central elements of the helicopter main rotor trim method is presented. Then, the CFD method as well as the improved trim strategy for helicopter main rotor flow-field simulation are described. Next, the effectiveness and efficiency of the improved trim method are discussed via the numerical results of two benchmark rotor cases. Finally, the conclusive remarks of this study are summarized in the last Section.

All simulations in this study were performed on 80 cores of the high-performance cluster of Politecnico

di Milano, CFDHUB, made up of Intel Xeon Gold 6248 CPU with speed of 2.5 GHz.

3. NUMERICAL METHODS

3.1. Flow solver ROSITA

The main features of the CFD code ROSITA (Rotorcraft Software ITALy) (Ref. 9) adopted in this study for simulating an unsteady flow around rotating blades in the systems of moving, overset, multi-block, structured grids are described in this part.

The ROSITA code numerically solves the three-dimensional unsteady compressible Reynolds-Averaged Navier-Stokes (RANS) equations in integral form with the one-equation Spalart-Allmaras (SA) turbulence model (Ref. 10). The convective fluxes of the equations are discretized by means of a cell-centered finite-volume implementation of Roe's scheme (Ref. 11), and second order accuracy in space is achieved using MUSCL (Monotone Upstream-centered Schemes for Conservation Laws) scheme with a modified version of Van Albada limiter (Ref. 12). The diffusive fluxes are calculated by a standard second order central difference scheme and the Gauss theorem. For unsteady simulation, the time advancement is carried out with an implicit dual-time method (Ref. 13), employing a second order backward differentiation formula to approximate the time derivative and a fully unfactored implicit scheme in pseudo-time. The equation for the state vector in pseudo-time is non-linear and is solved by sub-iterations accounting for a stability condition, as shown by Hirsch (Ref. 14) for viscous flow calculations. The generalized conjugate gradient (GCG), in conjunction with a block incomplete lower-upper preconditioner, is adopted to solve the resulting linear system.

The connectivity between the component grids is computed using the Chimera technique based on the modified Chesshire and Henshaw algorithm (Ref. 15). The Oct-tree and alternating digital tree data structure are employed to speed up the tagging process.

3.2. Trim method

In helicopter rotor analysis, the blade pitching, flapping, and lead-lagging motions are commonly described by the following Fourier series as a function of the azimuth angle φ :

$$(1) \quad \begin{cases} \theta(\varphi) = \theta_0 + \theta_{1c} \cos(\varphi) + \theta_{1s} \sin(\varphi) + \dots \\ \beta(\varphi) = \beta_0 + \beta_{1c} \cos(\varphi) + \beta_{1s} \sin(\varphi) + \dots \\ \delta(\varphi) = \delta_0 + \delta_{1c} \cos(\varphi) + \delta_{1s} \sin(\varphi) + \dots \end{cases}$$

Where θ is the pitch angle, β is the flap angle, δ is the lead-lag angle. In the present work, only the first harmonic term is considered. In general, the blades are assumed to move 'rigidly', and the flapping and lead-lag motions are ignored. Therefore, the rotor trimming state for forward flight rotor is affected by three independent control settings: collective pitch angle θ_0 , lateral cyclic pitch angle θ_{1c} , and longitudinal cyclic pitch angle θ_{1s} . Then, the trim equations can be expressed as:

$$(2) \quad \begin{cases} C_T(\theta_0, \theta_{1c}, \theta_{1s}) = C_T^{\text{target}} \\ C_{Mx}(\theta_0, \theta_{1c}, \theta_{1s}) = 0.0 \\ C_{My}(\theta_0, \theta_{1c}, \theta_{1s}) = 0.0 \end{cases}$$

In this work, a multi-dimensional "delta trim method" is introduced to solve the trim equations for rotor in forward flight conditions. As illustrated in Figure 1, the trimming process begins with the coarse simulation, in which the coarse grid system with large temporal resolution is used to calculate the low precision trimmed control angles. Subsequently, the accurate trim variables of the fine grid system with satisfactory temporal resolution can be determined at the fine simulation stage by using the trimmed settings computed at previous stage as initial guesses. Within the workflow of "delta trim method", the BET code and ROSITA solver are loosely coupled to obtain the trim settings of rotor blades via a Newton-Raphson iterator. The full descriptions of BET and standard "delta trim method" are given subsequently.

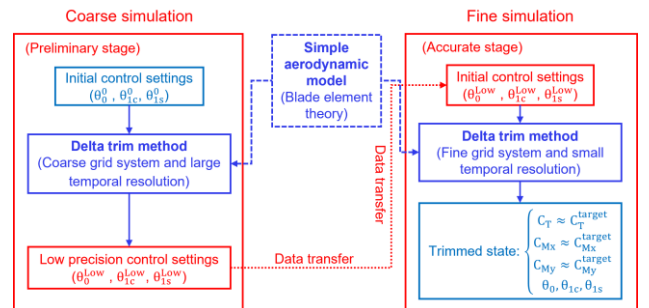


Figure 1. Multi-dimensional delta trimming procedure workflow implementation.

3.2.1. Blade element theory

As known, the BET is a simple aerodynamic model in helicopter rotor analysis (Ref. 1). It is assumed that the sectional air-loads at each blade element are produced by a two-dimensional airfoil. Rotor aerodynamic forces and moments can be obtained by integrating the air-loads of each blade section over the spanwise direction and averaging the results over a rotor revolution. To account for the mutual interaction between adjacent blade elements, an induced inflow model is introduced to correct the angle of attack of each airfoil section. With these treatments, the BET code can evaluate the aerodynamic performance of rotor with a certain precision and high efficiency, which makes it favorable to calculate the Jacobian matrix in the trim calculation. To illustrate this, a sketch of the BET model is presented in Figure 2, and a brief introduction follows.

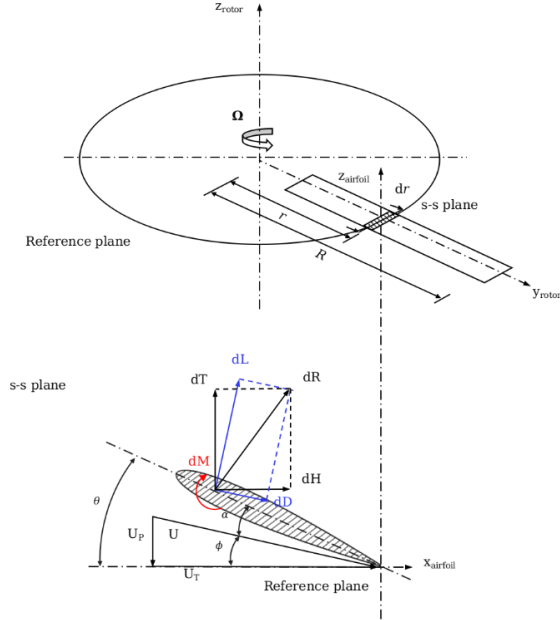


Figure 2. Illustration of blade element theory

The elementary contributions to the blade lift dL and dD are written as

$$(3) \quad \begin{cases} dL = \frac{1}{2} \rho C_L (U_P^2 + U_T^2) c dr \\ dD = \frac{1}{2} \rho C_D (U_P^2 + U_T^2) c dr \end{cases}$$

where the lift and drag coefficients of the airfoil section, C_L and C_D , can be obtained through the interpolation from a pre-prepared airfoil .C81 table or steady linearized aerodynamic theory. The inflow velocity components U_P and U_T are defined as

$$(4) \quad \begin{cases} U_P = \Omega r + \mu \Omega R \sin(\varphi) \\ U_T = \lambda \Omega R + r \frac{d\beta}{d\varphi} + \mu \Omega R \sin(\varphi) \cos(\varphi) \end{cases}$$

where, Ω represents the angular velocity, μ is the advanced ratio, R is the rotor radius, λ is the inflow ratio, which can be expressed as the sum of induced inflow ratio λ_i and climbing inflow ratio λ_c , $\lambda = \lambda_i + \lambda_c$.

The Drees linear flow model (Ref. 16) is adopted to calculate the induced inflow ratio.

$$(5) \quad \begin{cases} \lambda_i = \lambda_0 \left(1 + k_x \frac{r}{R} \cos(\varphi) + k_y \frac{r}{R} \sin(\varphi) \right) \\ \lambda_0 = \frac{C_T}{2\sqrt{\mu^2 + \lambda^2}} \end{cases}$$

where the inflow coefficients k_x and k_y are defined as

$$(6) \quad \begin{cases} k_x = \frac{4}{3} \left((1 - 1.8\mu^2) \sqrt{1 + \left(\frac{\lambda}{\mu}\right)^2} - \frac{\lambda}{\mu} \right) \\ k_y = -2\mu \end{cases}$$

The thrust dT of each narrow blade element can be expressed as function of induced inflow angle by projecting the dL and dD to the direction perpendicular to the rotor disk plane.

$$(7) \quad \begin{cases} dT = dL \cos(\varphi) - dD \sin(\varphi) \\ \varphi = \tan^{-1}(U_P / U_T) \end{cases}$$

By integrating dT over the rotor disk, the thrust T , the rolling moment M_x and the pitching moment M_y will be

$$(8) \quad \begin{cases} T = \frac{N_b}{2\pi} \int_0^{2\pi} \int_0^R dT d\varphi \\ M_x = \frac{N_b}{2\pi} \int_0^{2\pi} \int_0^R r \sin(\varphi) dT d\varphi \\ M_y = -\frac{N_b}{2\pi} \int_0^{2\pi} \int_0^R r \cos(\varphi) dT d\varphi \end{cases}$$

where N_b refers to the number of blades. The non-dimensional results follow the rules

Thrust coefficient C_T : multiply by $\frac{1}{\rho \pi \Omega^2 R^4}$

Moment coefficient C_M : multiply by $\frac{1}{\rho \pi \Omega^2 R^5}$

3.2.2. Standard “delta trim method”

The standard “delta trim method” is an incremental coupling algorithm that couples the CFD and BET approaches to calculate the trim variables. In an iterative fashion, the approach completely substitutes the CFD computed air-loads with BET solutions in the Jacobian matrix computation, resulting in a high efficiency trimming procedure. The implementation details are shown in Figure 3 and summarized in 6 steps.

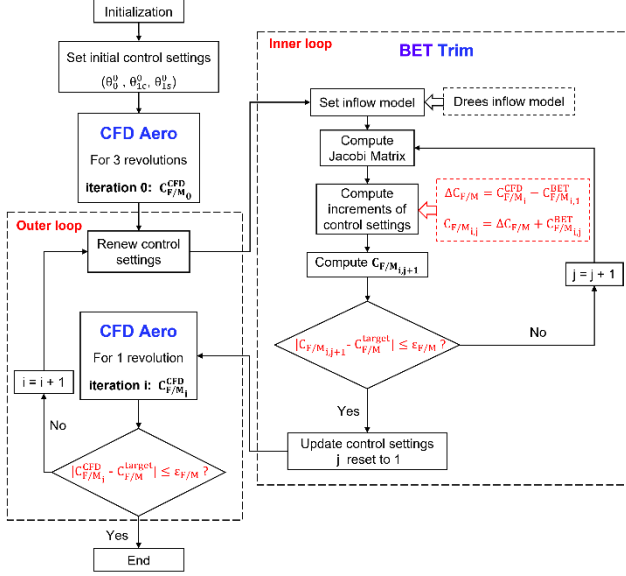


Figure 3: Flow chart of delta trimming procedure.

Step 1, Initialize the control settings: the initial control angles (θ_0 , θ_{1c} , θ_{1s}) could be set with the test data or estimated using the following equations given in Ref. 4.

$$(9) \begin{cases} \theta_0 = \frac{6C_T^{\text{target}}}{a\sigma} \left(\frac{1 + 3\mu^2/4}{1 - \mu^2 + \frac{9}{4}\mu^4} \right) - \frac{3}{2}\lambda \left(\frac{1 - \mu^2}{1 - \mu^2 + \frac{9}{4}\mu^4} \right) \\ \lambda = -\sqrt{\frac{\mu^4 + C_T^2 - \mu^2}{2}} \end{cases}$$

where σ is the rotor solidity, a is the lift-curve slope equals to 5.7. The initial cyclic pitch angles (θ_{1c} , θ_{1s}) are set to be zero.

Step 2, Initial calculation with CFD solver: two or three rotor revolutions are performed by the unsteady CFD simulation to obtain the initial values of thrust and moment coefficients: C_T^{CFD} , $C_{Mx_0}^{\text{CFD}}$ and $C_{My_0}^{\text{CFD}}$, where the superscript CFD represents the

CFD solver in the outer loop and the subscript 0 indicates that the trim cycle number is equal to zero.

Step 3, Inner loop with BET code: computing the Jacobian matrix using the BET solver. A small increment Δ is added to each control setting, and then the forward difference scheme is adopted to calculate the partial derivatives in the Jacobian matrix (the derivatives of θ_0 are taken as examples)

$$(10) \begin{cases} \frac{\partial C_T}{\partial \theta_0} \approx \frac{C_{T_{ij}}^{\text{BET}}(\theta_0 + \Delta, \theta_{1c}, \theta_{1s}) - C_{T_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s})}{\Delta} \\ \frac{\partial C_{Mx}}{\partial \theta_0} \approx \frac{C_{Mx_{ij}}^{\text{BET}}(\theta_0 + \Delta, \theta_{1c}, \theta_{1s}) - C_{Mx_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s})}{\Delta} \\ \frac{\partial C_{My}}{\partial \theta_0} \approx \frac{C_{My_{ij}}^{\text{BET}}(\theta_0 + \Delta, \theta_{1c}, \theta_{1s}) - C_{My_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s})}{\Delta} \end{cases}$$

where the superscript BET represents the BET solver in the inner loop and the subscript ij denotes the j -th inner loop iteration in the i -th outer loop. In this work, the Δ value is set to be 0.1° .

Step 4, Update trim variables: the control angles are computed by the Newton's iterative method, and the increment of control settings at each inner loop becomes:

$$(11) \begin{bmatrix} \Delta \theta_0 \\ \Delta \theta_{1c} \\ \Delta \theta_{1s} \end{bmatrix} = \begin{bmatrix} \frac{\partial C_T}{\partial \theta_0} & \frac{\partial C_T}{\partial \theta_{1c}} & \frac{\partial C_T}{\partial \theta_{1s}} \\ \frac{\partial C_{Mx}}{\partial \theta_0} & \frac{\partial C_{Mx}}{\partial \theta_{1c}} & \frac{\partial C_{Mx}}{\partial \theta_{1s}} \\ \frac{\partial C_{My}}{\partial \theta_0} & \frac{\partial C_{My}}{\partial \theta_{1c}} & \frac{\partial C_{My}}{\partial \theta_{1s}} \end{bmatrix}^{-1} \cdot$$

$$(12) \begin{bmatrix} C_T^{\text{target}} - \left(\Delta C_T + C_{T_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \right) \\ - \left(\Delta C_{Mx} + C_{Mx_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \right) \\ - \left(\Delta C_{My} + C_{My_{ij}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \right) \end{bmatrix}$$

$$\begin{cases} \Delta C_T = C_{T_i}^{\text{CFD}}(\theta_0, \theta_{1c}, \theta_{1s}) - C_{T_{i1}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \\ \Delta C_{Mx} = C_{Mx_i}^{\text{CFD}}(\theta_0, \theta_{1c}, \theta_{1s}) - C_{Mx_{i1}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \\ \Delta C_{My} = C_{My_i}^{\text{CFD}}(\theta_0, \theta_{1c}, \theta_{1s}) - C_{My_{i1}}^{\text{BET}}(\theta_0, \theta_{1c}, \theta_{1s}) \end{cases}$$

Step 5, Update thrust and moment coefficients with BET code: performing a BET computation with the updated control angles. The inner loop is about

to the end and the inner loop number j will be reset to 1 if the discrepancy between the computed results and the target values is less than the pre-defined convergence criteria, otherwise return to **Step 3** with the updated trim variables: $(\theta_0, \theta_{1c}, \theta_{1s})$

$$(13) \quad \begin{cases} \theta_0 = \theta_0 + \Delta \theta_0 \\ \theta_{1c} = \theta_{1c} + \Delta \theta_{1c} \\ \theta_{1s} = \theta_{1s} + \Delta \theta_{1s} \end{cases}$$

Step 6, Update thrust and moment coefficients with CFD solver: running the CFD solver for one revolution with the updated trim variables obtained in previous step and comparing the calculate thrust and moment coefficients $C_{T_i}^{CFD}$, $C_{M_{x_i}}^{CFD}$ and $C_{M_{y_i}}^{CFD}$ with the target values. The trim procedure stops if the convergence criteria are satisfied, otherwise repeats **Step 3** to **Step 5**. The convergence thresholds are set as follows:

$$(14) \quad \begin{cases} \left| C_{T_i}^{CFD} - C_{T_i}^{target} \right| \leq \varepsilon_1 \cdot C_{T_i}^{target} \\ \left| C_{M_{x_i}}^{CFD} - C_{M_{x_i}}^{target} \right| \leq \varepsilon_2 \\ \left| C_{M_{y_i}}^{CFD} - C_{M_{y_i}}^{target} \right| \leq \varepsilon_3 \end{cases}$$

where $\varepsilon_1 = 0.01$, $\varepsilon_2 = \varepsilon_3 = 1 \times 10^{-5}$ in this work.

4. RESULTS AND DISCUSSIONS

4.1. AH-1/OLS main rotor in forward flight

The OLS/TAAT (Ref. 17) in the German-Dutch Wind Tunnel (DNW) is considered to assess the multi-dimensional “delta trim method”. The experiment involved a 1/7-scaled AH-1 helicopter main rotor. More information about the rotor geometry and test conditions is reported in Table 2. The blade motion given by the experiment is expressed as

$$(15) \quad \begin{cases} \theta(\varphi) = 6.14 + 0.9\cos(\varphi) - 1.39\sin(\varphi) \\ \beta(\varphi) = 0.5 - 1.0\cos(\varphi) \end{cases}$$

Table 2: Geometric properties and test conditions of the AH-1/OLS main rotor (Ref. 17).

Characteristic	AH-1/OLS
N_b	2
Blade planform	Rectangular
Blade section	BTH-540
R	0.958 m
c	0.1039 m
θ_{tw}	Linear, -8.2°
R_c	0.182R
Test point	10014
μ	0.164
α_s	0°
Ω	235.7 rad/s ($M_T = 0.664$)
C_T^{target}	0.0054
$C_{M_x}^{target}$	0.00
$C_{M_y}^{target}$	0.00

A moving embedded grid system is designed for the present study to simulate the motion of rotor blades in forward flight. It considers a far-field background grid (FG), a near-field background grid (NG), a wake grid (WG), and two identical blade grids (BG), as illustrated in Figure 4. The far-field grid is generated to represent the flow domain far from the rotor, where outer boundaries are located 2R (above), 4R (below), and 5R (radial) away from the blade hub. The near-field grid is created to model the flow region close to the blades. The wake grid is built to capture the rotor wake. The body-fitted grid is modeled with a C-H topology with non-slip boundary condition on the blade surface. The wall distance of the first layer of blade surface is set to $1 \times 10^{-5} c$ so that the y^+ value is less than 1.

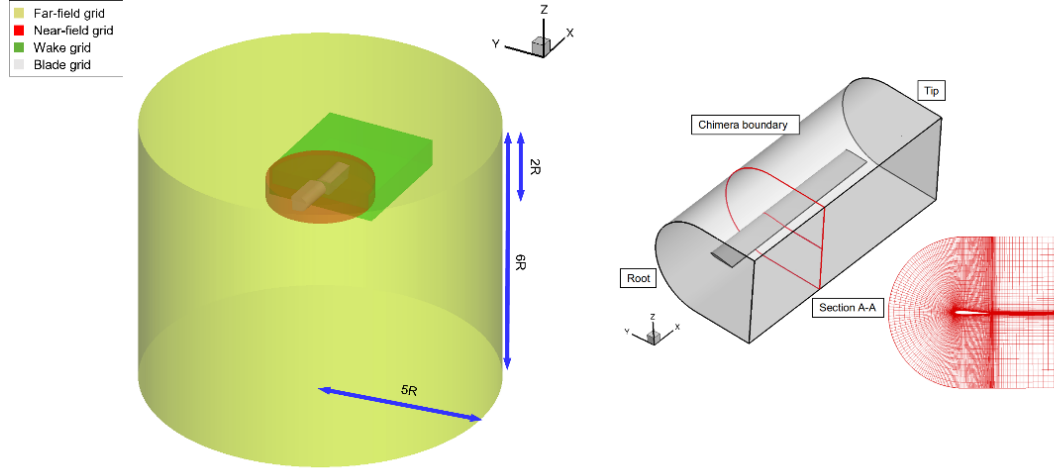


Figure 4. Overview of the overset grid system for AH-1/OLS rotor simulation.

Two overset grid systems with the same geometry and topology, increasing the mesh size from 6.9 to 9.5 million, are employed to investigate the multi-dimensional “delta trim method”, and labeled coarse and medium, respectively. The medium grid system uses the same blade grid as the coarse grid system

but finer background and wake grids. In detail, the blade has the grid cells of 292 (chordwise) $\times$ 132 (spanwise) $\times$ 60 (normal). The different background and wake grid resolution details are summarized in Table 3 and Table 4, respectively.

Table 3: Details of the background grids (t: circumferential, r: radial, z: normal, minimum spacing is outlined in terms of the airfoil section chord c).

Mesh	N_{tot}	N_t	N_r	N_z	Δt	Δr	Δz	Label
FG1	1520640	288	63	66	0.11	0.5	0.5	Coarse
FG2	2585088	288	84	88	0.11	0.25	0.25	Medium
NG1	336960	360	36	16	0.09	0.4	0.4	Coarse
NG2	1020600	360	72	30	0.09	0.2	0.2	Medium

Table 4: Details of the wake grids (minimum spacing is outlined in terms of the airfoil section chord c).

Mesh	N_{tot}	N_x	N_y	N_z	ΔX	ΔY	ΔZ	Label
WG1	314184	114	106	26	0.3	0.3	0.3	Coarse
WG2	1113600	174	160	40	0.2	0.2	0.2	Medium

Table 5 reports the trimmed control angles obtained using the standard “delta trim method” with different grid spatial and temporal resolutions. It is known that finer background grid systems and temporal resolutions can provide more accurate predictions of blade air-loads, especially in the BVI-dominated case.

However, as can be observed in Table 5, their influences on the trimmed control angles are negligible, suggesting that coarse simulations can be used to speed up the standard “delta trim method”. Based on this idea, the multi-dimensional “delta trim method” is derived.

Table 5: Trimmed results using the standard “delta trim method”.

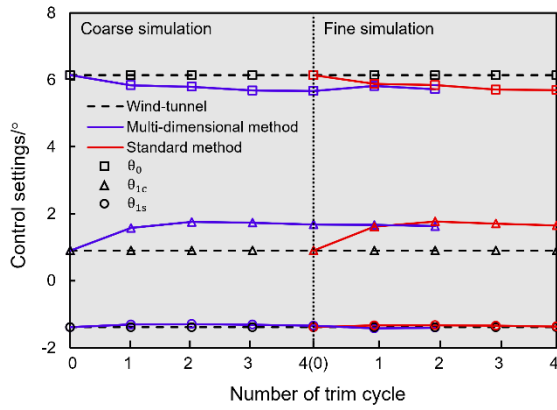
Simulation resolutions		Trimmed control angles			Maximum error to medium grid
Grid spatial	Temporal	θ_0	θ_{1c}	θ_{1s}	$ \epsilon_{max} $
Medium	1°/step	5.690°	1.630°	-1.382°	—
Coarse	1°/step	5.696°	1.628°	-1.384°	0.14%
	4°/step	5.667°	1.681°	-1.341°	1.76%

To assess the proposed trim method, simulations are performed following the test configurations in Table 6, where the standard “delta trim method” is conducted for comparison. Figure 5 shows the convergence history of the two trim methods, and their CPU time costs are compared in Table 7. The trimming process of the multi-dimensional “delta trim method” converges after six trim cycles (four coarse and two fine simulations), while the standard “delta

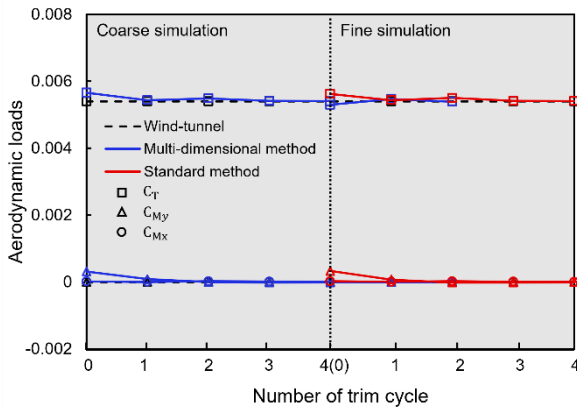
trim method” requires only four trim cycles (four fine simulations). However, the multi-dimensional method saves approximate 12% CPU hours compared to the standard method. This indicates that although the multi-dimensional trimming calculation requires more trim cycles to achieve convergence, it is less computational expensive than the standard “delta trim method”.

Table 6: Test configurations for AH-1/OLS rotor 10014 simulations.

Delta trim method	Grid system	Temporal resolution	Simulation type
Standard	FG2+NG2+WG2+2BG	1°/step	Fine
Multi-dimensional	FG1+NG1+WG1+2BG	4°/step	Coarse
	FG2+NG2+WG2+2BG	1°/step	Fine



(1) Trim variables: θ_0 , θ_{1c} , θ_{1s}



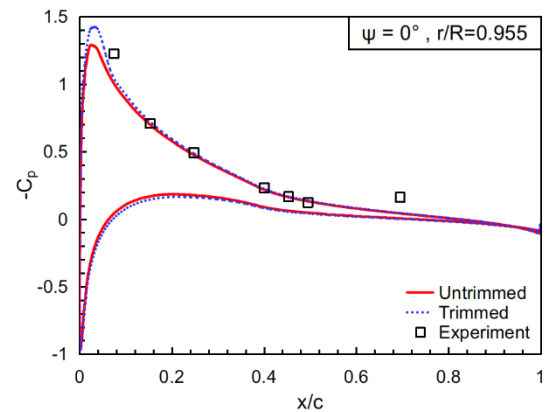
(2) Blade air-loads: C_T , C_{My} , C_{Mx}

Figure 5. Convergence history of trim variables and blade air-loads for AH-1/OLS rotor 10014 case.

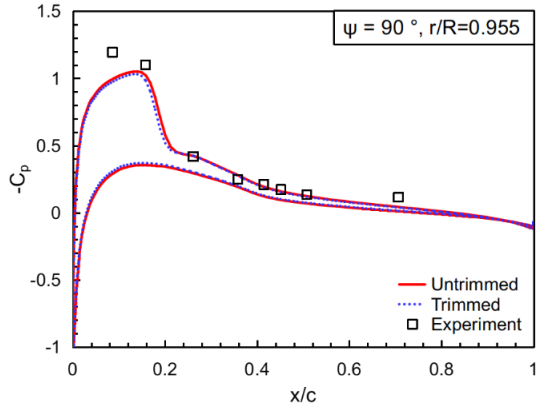
Table 7: CPU run-time of two trim methods for AH-1/OLS rotor 10014 case.

Delta trim method	CPU time	Relative ratio
Standard	11062 h	1.00
Multi-dimensional	9758 h	0.88 (-12%)

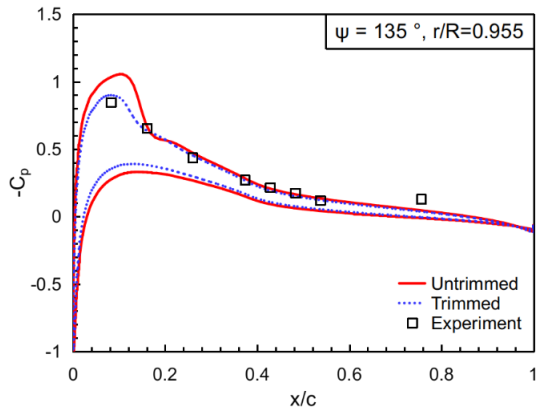
The C_p distributions over the radial position of $r/R = 0.955$ at 0° , 90° , 135° and 180° azimuths are displayed in Figure 6, where the results with the untrimmed and trimmed control angles are compared against the measured data (Ref. 18). From these plots, the results calculated using the trimmed control settings show a significant improvement in C_p prediction, especially for the data on the leading edge of the blade upper surface, demonstrating the effectiveness of the multi-dimensional “delta trim method” for rotor aerodynamic prediction.



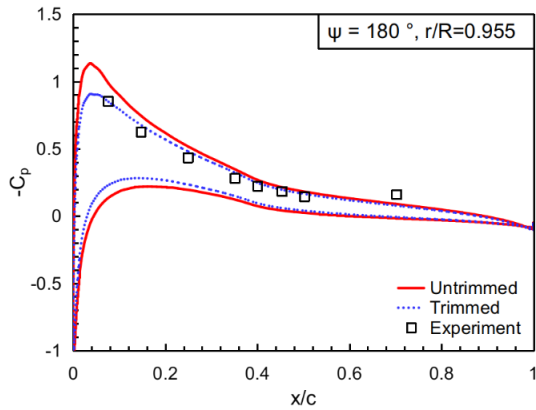
(1) $\phi = 0^\circ$



(2) $\varphi = 90^\circ$



(3) $\varphi = 135^\circ$



(4) $\varphi = 180^\circ$

Figure 6. Pressure coefficient comparisons on different blade cross-section at $r/R=0.955$ for various azimuth angles.

4.2. HART-II main rotor in descent flight

Within the framework of the second Higher Harmonic Control Acoustic Rotor Test (HART-II), a highly instrumented 40% Mach scaled Bo-105 rotor test was conducted in the open $8\text{ m} \times 6\text{ m}$ test section of the DNW (Ref. 19). The aim of the HART-II program was to study the rotor wake and its development within the entire rotor disk. The baseline (BL) case of the HART-II experiment is employed as it is a descent flight dominated by BVI phenomena. More descriptions about the rotor geometry and test conditions are reported in Table 8.

Table 8: Geometric properties and test conditions of the HART-II main rotor (Ref. 19).

Characteristic	HART-II
N_b	4
Blade planform	Rectangular
Blade section	NACA23012mod
R	2.0 m
c	0.121 m
θ_{tw}	Linear, -8.0°
R_c	0.22R
Test point	Baseline (BL)
μ	0.15
α_s	4.5°
Ω	109 rad/s ($M_T=0.64$)
T^{target}	3300 N
M_x^{target}	20 N·m
M_y^{target}	-20 N·m

The grid discretization is achieved using a multi-block overset grid system with Chimera technology. The grid system includes a far-field background grid (FG), a near-field background grid (NG), and four identical body-fitted blade grids, as depicted in Figure 7. The far-field background grid is created to represent the flow domain far from the rotor. A uniform Cartesian grid is built as the near-field background grid to model the flow region close to the blades, as well as to capture the rotor wake. The body-fitted grid is generated with a C-H topology type with the non-slip boundary on the blade surface. The y^+ value is set to less than 1.

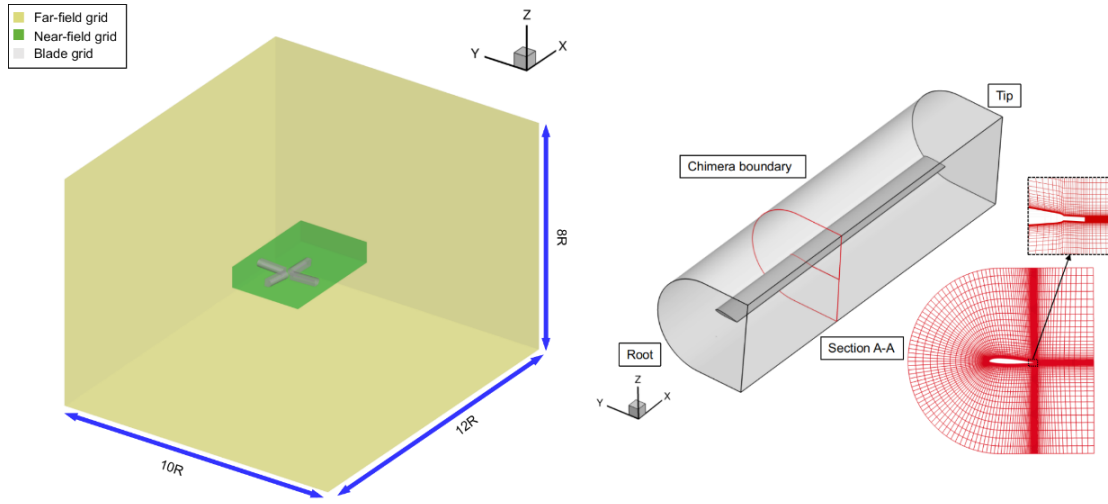


Figure 7. Overview of the overset grid system for HART-II rotor simulation.

The multi-block structured grid system for the HART-II rotor has a total of 12.6 million cells with 0.9 million for the far-field background grid, 6.7 million cells for the near-field background grid, and 1.2 million cells for each of the body-fitted blade grid with the dimensions of 173 (chordwise) $\times$ 125 (spanwise) $\times$ 50 (normal). Moreover, a coarse grid system with 7.5 million cells is created for the trimming process,

where the far-field background grid of 0.6 million cells and the near-field background grid of 2.0 million cells. More detailed grid information for background grids is summarized in Table 9. The HART-II BL simulations are carried out according to the test configurations in Table 10, where the standard “delta trim method” is performed for comparison.

Table 9: Details of the background grids (minimum spacing is outlined in terms of the airfoil section chord c).

Mesh	N_{tot}	N_x	N_y	N_z	ΔX	ΔY	ΔZ	Label
FG1	573056	88	88	74	0.3	0.3	0.3	Coarse
FG2	925552	102	102	88	0.2	0.2	0.2	Medium
NG1	1992000	250	166	48	0.248	0.248	0.248	Coarse
NG2	6732000	374	250	72	0.165	0.165	0.165	Medium

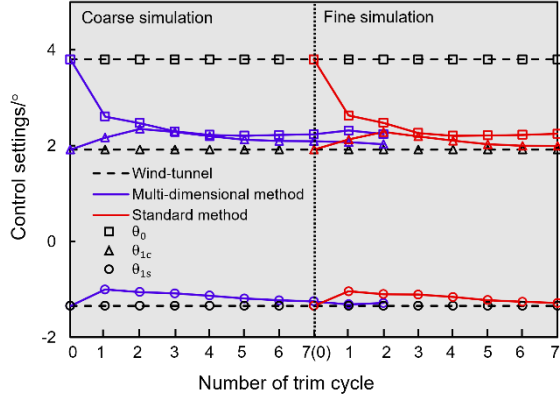
Table 10: Test configurations for HART-II rotor BL simulations.

Delta trim method	Grid system	Temporal resolution	Simulation type
Standard	FG2+NG2+4BG	1°/step	Fine
Multi-dimensional	FG1+NG1+4BG	4°/step	Coarse
	FG2+NG2+4BG	1°/step	Fine

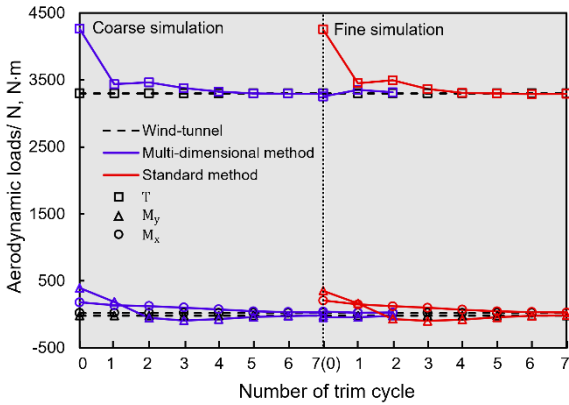
Table 11 compares the experimental control angles and those obtained by the multi-dimensional. It is observed that the lateral (θ_{1c}) and longitudinal (θ_{1s}) pitch cyclic angles agree well with the measured values (Ref. 19), but the collective (θ_0) pitch angle is underpredicted. This may be related to the blade elasticity that was not considered. Figure 8 illustrates the convergence history of the standard and multi-dimensional delta trimming processes.

Table 11: Trimmed data for HART-II rotor BL case.

Case	Experiment	Present Calculation
θ_0	3.80°	2.24°
θ_{1c}	1.92°	2.03°
θ_{1s}	-1.34°	-1.28°
T	3300 N	3315.6 N
M_x	20 N·m	26.8 N·m
M_y	-20 N·m	-21.5 N·m



(1) Trim variables: θ_0 , θ_{1c} , θ_{1s}



(2) Blade air-loads: T , M_y , M_x

Figure 8. Convergence history of trim variables and blade air-loads for HART-II rotor BL case.

Table 12 outlines their CPU time cost. Although the present multi-dimensional “delta trim method” requires more trim cycles to achieve convergence than the standard “delta trim method”, it saves 31% of CPU hours due to the use of coarse simulations, which further demonstrates its higher efficiency.

Table 12: CPU run-time of two trim methods for HART-II rotor BL case.

Delta trim method	CPU time	Relative ratio
Standard	20846 h	1.00
Multi-dimensional	14305 h	0.69 (-31%)

Figure 9 shows the trimmed behavior of CFD computations on $C_n M^2$ obtained at 87% radial station ($r/R=0.87$) and compares it with the measurements (Ref. 19) and the untrimmed results calculated using the experimental trim angles. The general shape of the trimmed solution is found to correlate much better with the experimental data than the untrimmed

results, although some details of the measurements are still not well reproduced due to the coarseness of the employed grid system and the neglected blade elasticity (Ref. 20). Overall, the trimmed control settings provide a satisfactory result for the simulation of the HART-II rotor in BL condition.

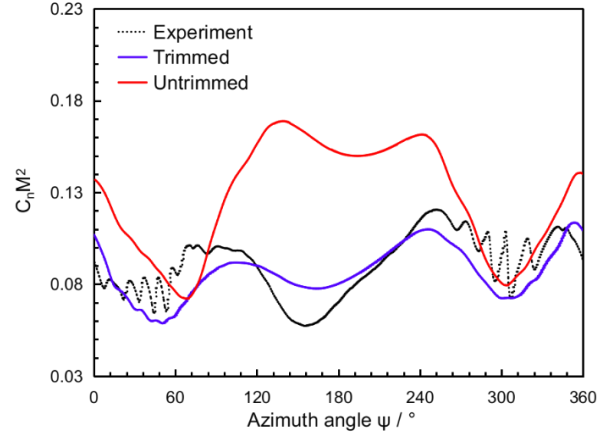


Figure 9. $C_n M^2$ variations at $r/R=0.87$

5. CONCLUDING REMARKS

In this work, the multi-dimensional “delta trim method” has been developed for helicopter main rotors in forward flight and the rotor trimming process is presented in detail. The method used a combination of multi-level grid spatial and temporal resolutions to speed up the trimming procedure. The method consists of two stages: a coarse simulation in the preliminary stage to obtain a more accurate initial guess for the next stage; and a fine simulation in the accurate stage to achieve the precise trimming. The AH-1/OLS rotor and HART-II rotor in forward flight conditions have been investigated with the multi-dimensional “delta trim method”. The trimmed results were in good agreement with the wind-tunnel test data. Meanwhile, the trim method saved about 12% and 31% CPU time cost in the AH-1/OLS rotor and HART-II rotor cases, respectively, compared to the standard “delta trim method”.

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