# A FRAMEWORK FOR ACCURATE AND EFFICIENT CFD ANALYSIS OF HELICOPTER ROTORS

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## Introduction

The numerical simulation of the flow around fixed-wing aircraft has been the subject of several research works, see [1], amongst others. Modern CFD methods can, at design conditions, predict with good accuracy the wing lift and with fair accuracy total wing drag. For rotary-wing aircraft, however, the situation appears to be more complicated and CFD analysis appears to be significantly harder [2-7].

There are two main reasons contributing to this situation: (i) the flow physics is much more complicated in terms of fluid mechanics phenomena and (ii) there is a strong link between the aerodynamics and dynamics of the rotor blades. CFD methods have to cope with strong vortices interacting with each other as well as the rotor blades, formation of a complex spiral wake behind the rotor, transition to turbulence and wide variations of the Mach and Reynolds numbers around the azimuth. The link between the blade aerodynamics and dynamics is through the balance of forces acting on the rotor. This is known as the rotor trimming problem which further complicates the numerical simulation of rotor flow. Regardless of the moderate success of CFD, several experimental efforts have been put forward aiming to enhance out understanding of the rotor aerodynamics and also provide data-sets for validation of CFD methods [9-11].

## Method Description

In view of the above, the main objective of this work is to present the extensions needed for converting a CFD method to one suitable for simulating rotors. This framework for rotorcraft CFD is built using several modules. At first, hovering rotor cases can be treated as steady-state computations by changing the frame of reference used for the calculations to a non-inertial, blade-fixed one [3]. A forward-flight module, which solves the governing equations in a fixed inertial frame of reference, is also needed. This module uses a moving and deforming mesh approach which accounts for isolated helicopter rotors with fully-articulated rigid rotor blades, i.e. the blades carry out periodic flap, lead-lag and pitch mo-

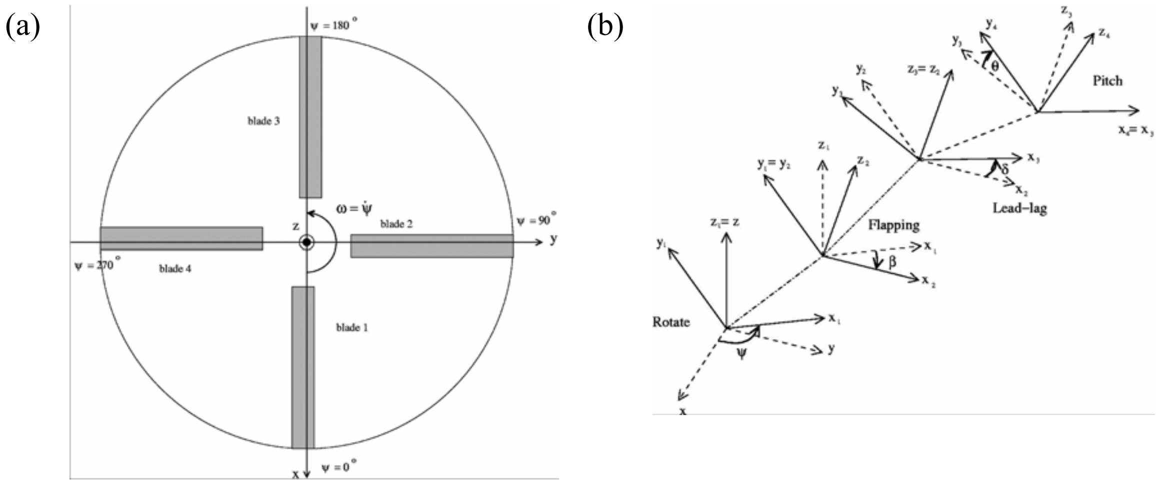



Fig. 1. (a) rotor disk and (b) hinge transformations used within the current CFD framework

tions. As a first approximation, elastic blade deformations are neglected.

Figure 1a presents a schematic of the frame of reference used in the forward-flight formulation. The rotor revolves around the z-axis in counter-clockwise fashion and the azimuthal position is denoted by ψ. The rotor blades are numbered and the first blade is located on the positive side of the x-axis. Figure 1b shows the coordinate transformations relating the fixed inertial frame of reference to a blade-fixed frame of reference.

Within the mesh-deformation module, a technique that deforms a multi-block structured mesh using a combination of rigid mesh motion (mesh blocks attached to a blade move with that blade) and grid deformation is used. The mesh deformation is based on the Trans-Finite Interpolation (TFI) method. Figure 2 presents the construction of the moving/deforming grid around a four-bladed rotor. Starting from the blade surface (Figure 2a) the method automatically selects a set of blocks around the blade and marks these for rigid, un-deformed motion (Figure 2b). This is repeated for all blades around the hub and the final assembly is shown in Figure 2c. The mesh outside the surfaces is deformed using the TFI method.

In addition to the above, a trimming algorithm is also needed for forward-flight simulations. A basic trimming method, as documented by Seddon [8] is used. The algorithm uses the computed loading for each blade to trim the rotor on a “once-per-revolution” basis. This type of

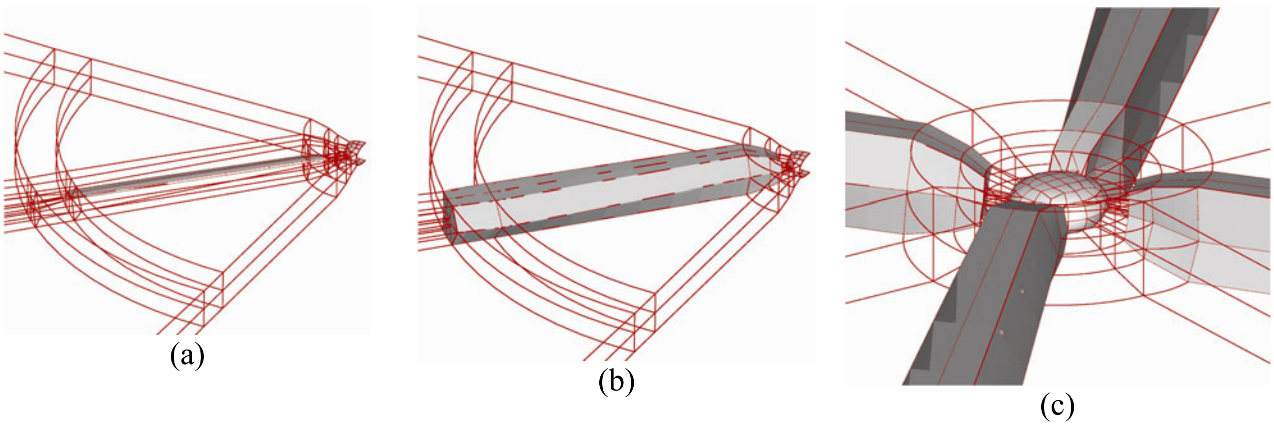



Fig. 2. (a) blade surface and multi-block boundaries for the ONERA 7A rotor. (b) rigid blocks around the blade and (c) rigid blocks and hub for the full rotor case

coupling of the rotor dynamics and the aerodynamics is commonly referred to as “loose-coupling” and is adequate for analysis of new rotor designs both at hover and forward flight conditions. It is not suitable, however, for the analysis of manoeuvring rotors.

## Validation test cases – hovering rotors

Validation of the current framework has been carried out using wind tunnel data for the hovering model rotors tested in [9,10] and for the high-speed forward-flying model rotor tested in [11]. The first hover validation case is the well-known Caradonna and Tung [9] two-bladed rotor with straight untwisted blades (aspect ratio 6, NACA0012 sections) at a collective pitch of 8° and a tip Mach number of 0.44.

Figure 3 presents the computed surface pressure coefficient at two radial stations along with the experimental data of Caradonna and Tung. [9].

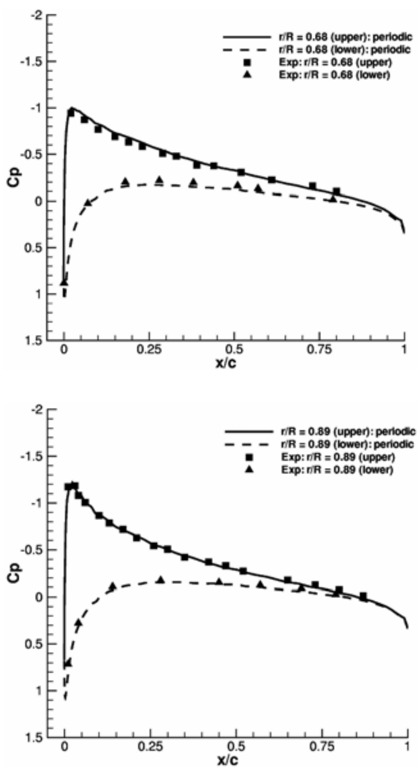



Fig. 3. Comparison between CFD and experiments for the surface pressure distribution of the Caradonna-Tung model rotor (8° and a tip Mach number of 0.44)

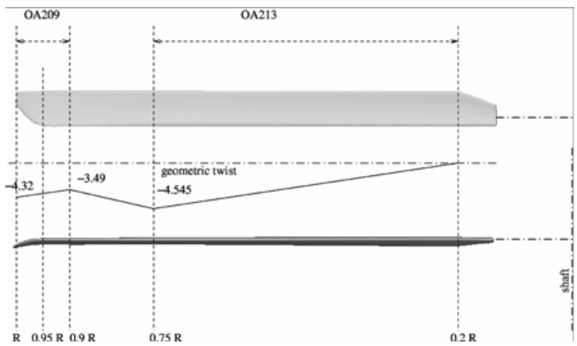


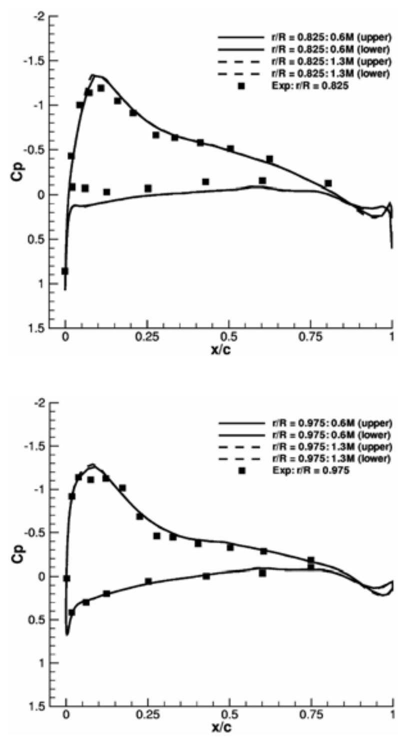

Fig. 4. Details of the ONERA 7AD1 model rotor [10]

The agreement is very good for both radial stations and the simulation captures well the peak values of the surface pressure coefficient as well as the recovery of the Cp along the chord of the blade.

Although the Caradonna and Tung model rotor is of a relatively simple planform, the approach described in this paper is quire general and can be applied to advanced rotor designs.

Figure 4 presents the geometric details of the ONERA 7AD1 rotor which was extensively

(a)




(b)

Fig. 5. Comparison between CFD and experiments for the surface pressure distribution on the ONERA 7AD1 rotor blade [10] (8° and a tip Mach number of 0.44)

tested during the HELISHAPE campaign [10]. The blade has an aspect ratio of 15 and for this case the tip Mach number is 0.6612. Figure 5 presents the comparison between CFD and experiments at two radial stations and again excellent agreement is obtained. The station shown in Figure 5a corresponds to an inboard location while the radial station of Figure 5b is in on the tapered section of the blade where anhedral is used.

## Validation cases -forward flying rotors

In contrast to hovering rotors where the geometry of the rotor is fixed, forward flying rotors require substantial mesh deformations to account for the motion of the blade due to the cyclic, flapping and lead-lag harmonics. The benefit of the current approach is highlighted in Figure 6 where snapshots of the grid during the computation are shown. As can be seen, the mesh quality near the blade where rigid block motion is used is comparable to the quality of the initial un-deformed grid while substantial deterioration can be seen if TFI is use through out the domain.

Figure 7 presents the surface pressure coefficient for the advancing side of non-lifting rotor at high speed flight. The agreement with the experiments of ONERA [11] is excellent and the current method clearly captures the strong shock formed near the tip of the rotor. Figure 8 presents indicative results for a fully articulated forward-flying rotor. Although no experimental data are available for this case all degrees of freedom associated with the rotor's hinges are present. The blue-shaded areas of Figure 7 correspond to the disk plane of the initial rotor configuration while the grey-shaded areas show the location of the blades at various azimuth angles. The corresponding Cp distribution plots indicate a slightly un-trimmed rotor.

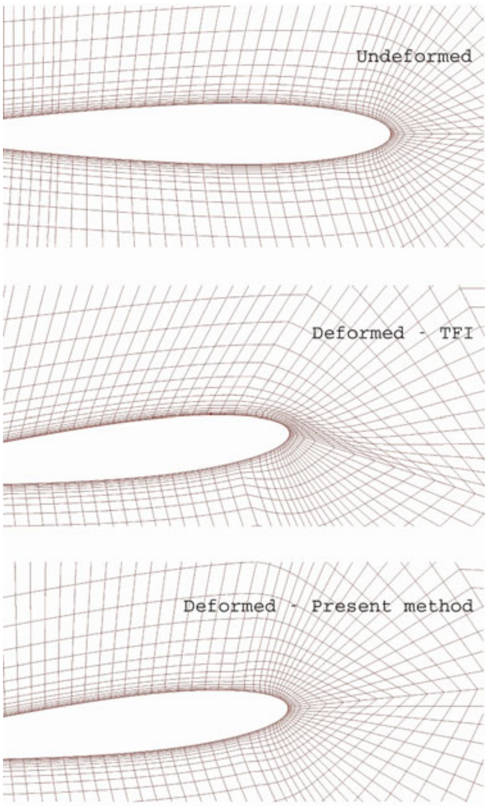



Fig. 6. Snapshots of the CFD grid during forward flying computation with cyclic harmonics

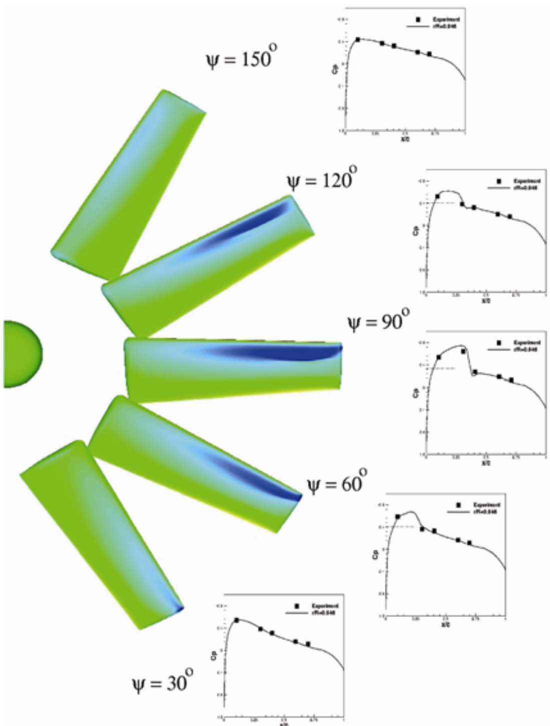



Fig. 7. Surface pressure distribution for the non-lifting ONERA rotor at high speed forward flight ($M_{tip}$ = 0.628, μ = 0.45) [11]

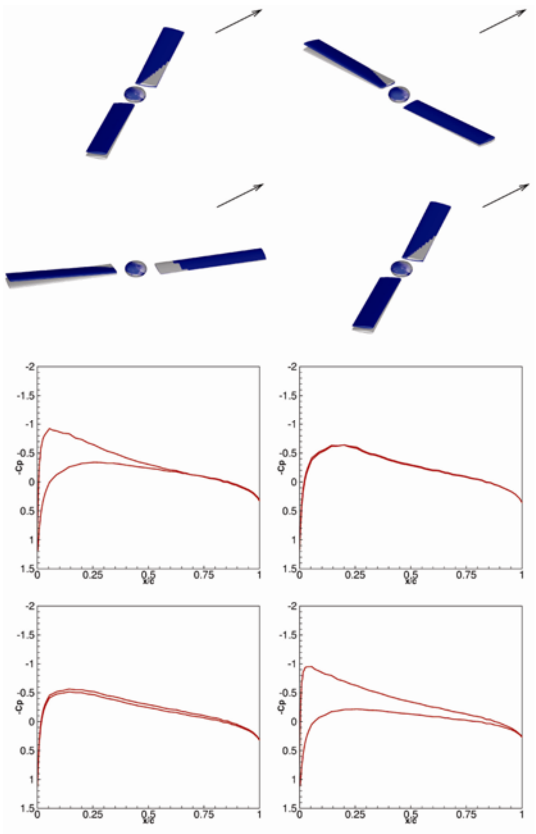


Fig. 8. CFD results for a fully articulated rotor in forward flight. The blue shade represents the rotor disk plane and the position of the blades is shown in gray. The CFD predictions for the Cp at a radial station of 70%R are shown indicating an un-trimmed rotor ($M_{tip} = 0.60$, $\mu = 0.35$, $\theta_s = -2.0°$, 2.0° coning, 3.0° longitudinal cyclic, 1.5° lateral cyclic, 2.0° longitudinal flapping)

## Trimmed rotor demonstration

Figure 9, presents the trim-history of the thrust coefficient, the collective and conning angles of a hovering rotor trimmed to a thrust coefficient of 0.005. As shown, the initial guess for the collective and conning angles resulted in an overestimation of the loading. Both angles were quickly adjusted using a Newton-Raphson method so that the desired loading is achieved. About three thousand iterations were necessary for this case and this number is comparable to the iterations required for the computation of the hovering rotor case without the trimming method. Even with this small overhead, the required CPU time is only 3 hours on 8 Pentium 4 processors.

## Conclusions

A CFD framework has been presented for the analysis of hovering and forward-flying rotors. Three main modules have been described, namely, hover module, forward-flying method and trimming method. Each module has been carefully validated using data available in the literature. Hovering rotors are relatively easy to compute due to the steady state formulation of the problem. Forward-flying rotors, however, require much higher CPU times and in addition,

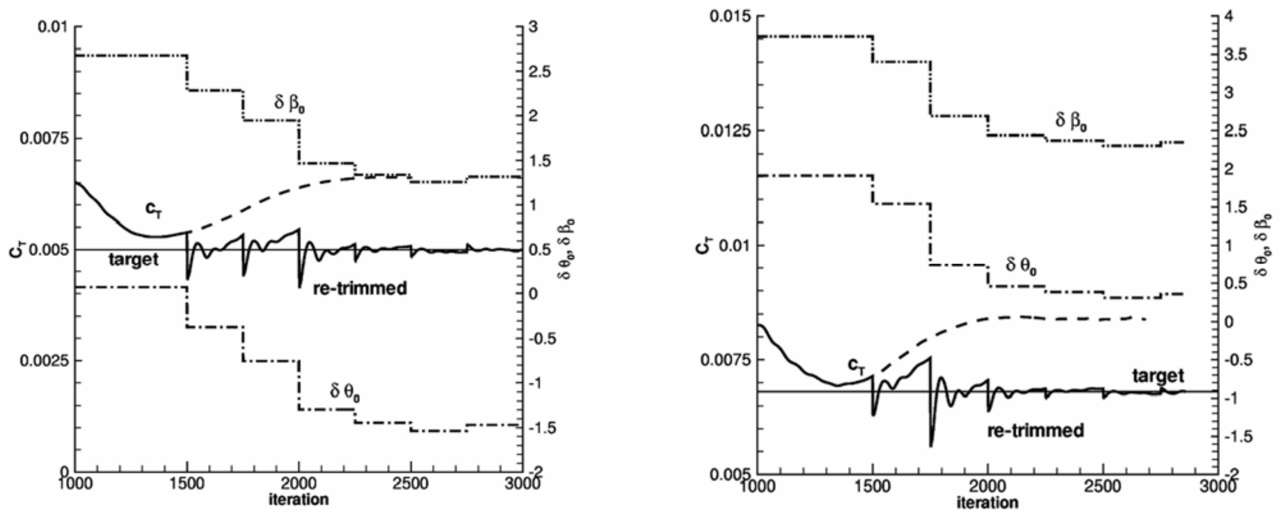



Fig. 9. Convergence history of the thrust coefficient, as well as the collective and coning angles for a rotor trimmed at a specified loading

the trimming requirements put restrictions on the allowed time step. In the future, efforts will be directed towards efficient techniques to tackle the forward-flying problem. In particular, taking advantage of the quasi-periodic flow around the rotor should allow for a significant reduction of the CPU time. Finally, adequate experimental data are necessary for validation and these should include not only surface pressure measurements but flow-field investigations near the blade and in the wake.

## Acknowledgements

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