TOWARD A COMPUTATIONAL FRAMEWORK FOR ROTORCRAFT MULTI-PHYSICS ANALYSIS: ADDING COMPUTATIONAL AERODYNAMICS TO MULTIBODY ROTOR MODELS

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Abstract

This paper presents a computational framework for the integrated simulation of complex multi-physics problems. It results from interfacing existing structural dynamics, multidisciplinary software and different computational fluid dynamics codes by means of a newly developed, broadly general communication scheme that accounts both for solution synchronization and field interpolation. A first application to the fluid structure interaction problem based on a free wake code is presented. More complex applications will be presented in the near future.

Introduction

Rotorcraft integrated dynamics analysis is a very difficult task, which showed only partially successful results in current practice. However, the need for reliable tools that couple the structural dynamics and the aerodynamics of rotorcraft is strong, and satisfactory results cannot be obtained with existing software. It is worth recalling that a general reduction of vibratory loads transmitted to the cabin and of the generated noise are perceived as major goals to be achieved by the rotary wing industry. The Blade Vortex Interaction (BVI) problem is dominated by the "missing distance" parameter, which is strongly influenced by tip vortex trajectory, blade elastic deformation and induced velocity distribution (see Yu [1]). As stated in the papers of Bousman [2], in the last fifteen years rotor loads prediction capability improved, but, especially for vibratory loads, the comparison of numerical methods with flight tests is still not satisfactory. The load prediction problem has been correctly characterized by Dr. W. Johnson [2] who said, almost twenty years ago, in 1985: "for a good prediction of loads it is necessary to do everything right, all of the time. With current technology it is possible to do some of the things right, some of the time". This statement calls for more and more integrated analysis tools. Both theory and computational tools are improving dramatically, not to mention hardware capabilities. It appears that time has come to try putting everything together and see how far we are from complete deformable rotorcraft aero-servoelastic analysis. This is required to achieve the major goals of rotorcraft dynamics prediction, e.g. those related to control systems analysis and design, flight control system synthesis, vibration control, load reduction and flutter suppression. Among the works that are going in this direction, those by Pomin and Wagner [3], van der Ven and Boelens [4], Yang et al. [5] deserve a mention.

The structural dynamics problem is posed on sound foundations, and it has been developed to a high degree of accuracy. Today, the multibody approach to the simulation of the dynamics of rotor blades, rotors and entire rotorcraft is gaining broad acceptance both in the academic and in the industrial field [6, 7]. At the same time, CFD for rotors is gaining momentum and it is becoming a practical tool for helicopter rotor aerodynamics analysis and design. A new ideal tool, required to tackle this challenge, needs to combine all the expertise developed in each field to reach a satisfactory global solution. As a consequence, it appears reasonable to prospect the possibility and the feasibility of effective and efficient coupling of existing, state-of-the-art software. This paper presents a viable solution for coupling existing software in an integrated solution scheme, without particular requirements on the functionality of the codes that are being coupled. The presented approach allows the user to choose in a

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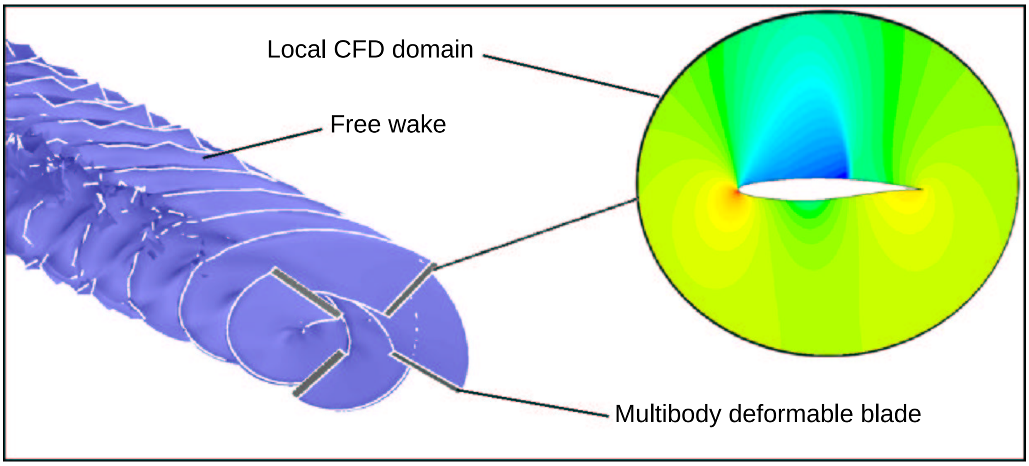


Figure 1: Domain decomposition on a physical basis.

wide range of possible coupling schemes, going from what is known as "tight coupling" of the entire multidisciplinary problem, up to "loose coupling" where there is no feedback interaction between the different fields [8]. The tight procedure is nonetheless implemented using separate pieces of software. This allows to achieve the best trade-off between accuracy and efficiency, depending on the requirements of the problem under investigation, while dealing always with the same set of one's preferred tools. Currently, only the time marching solution of initial value problems is addressed.

Approach

Until recently, the problem of modeling the aerodynamic forces in aeromechanics comprehensive codes for rotors has been mainly tackled by means of the classical blade section element theory, coupled to an inflow model, especially within the multibody approach [9, 7]. However, it is well known that there are flight conditions where these simplified models fail at giving correct prediction, especially when vibratory loads and noise problems are addressed [2]. Typical comprehensive rotorcraft codes, which heavily rely on simplified theories for the aerodynamics, enabled the development of a rational engineering process, yet allowing significant uncertainties, costly testing and unpleasant surprises, as reported by Caradonna [10].

The main object of this work is the extension of the modeling capability for both, the computation of the aerodynamic loads, and the description of the flow field. In fact, if the synthesis of automatic control systems for the noise reduction needs to be addressed, it is necessary to model also the flow field and more precisely the position of vortical elements. The idea pursued here is to create a toolbox of modeling paradigms for aerodynamic loads prediction, where each one is capable to address by itself a specific aspect of the fluid flow, but at the same time to interact with other paradigms to achieve a higher degree of precision for the whole model. The goal is to develop a sort of "domain decomposition on a physical basis" of the flow field (Figure 1), so that, depending on the specific weight of each phenomena inside the flow field, it is possible to choose the model which represents an optimal trade-off between accuracy and computational costs.

To realize this concurrent simulation environment, an approach based on the creation of a new process, called "broker", is proposed. The broker is used to synchronize the execution of all the other participating processes. The communications are based on the popular Message Passing Interface (MPI) software communication package, available in open source form on virtually any platform.

As soon as all the other processes join the pool, the broker schedules their correct execution and takes care of exchanging the required data, according to "blocks" defined for each communication pattern. This allows highly heterogeneous software to participate to the execution pool, ensuring that only the data specific to each participant is visible to them and thus minimizing the communication effort. Moreover, whenever required, the broker can be instructed on how to interpolate the data in field form that it is required to pass. This frees the participating processes from the need to know whom they are communicating with, and thus to implement a common intercommunication format.

The structural dynamics and multi-field participants to the execution pool need not be unique: there may be multiple concurring structural models, e.g. multiple rotorcraft in a helicopter interference simulation, or the same structural model can present multiple communication patterns, e.g. one for each rotor in a multi-rotor model.

At the same time, the CFD participants need not be unique: there may be multiple concurring aerodynamics domains, e.g. one Euler model for each blade, and one free-wake model that provides far-field boundary conditions for all (Figure 1).

The envisaged communication patterns are sketched in Figure 2 and described in Table I; only the "driver" structural pattern is currently implemented. The "driven" pattern is intended to couple the current multibody analysis simulation, based on an implicit integration scheme, to an explicit integration process that models fast dynamics such as crash landing or impact problems.

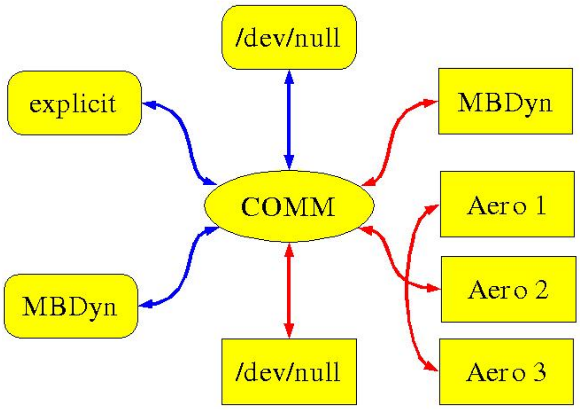


Figure 2: Communication Patterns

The aim of this work is to allow the integrated solution of multi-field initial value problems, with the final objective of simulating transients in rotorcraft analysis. In fact, integrated accurate rotorcraft analysis are inherently transient, because of the concurring effect of different sources of time-dependent excitation operating at different time periods, e.g. main and tail rotor in conventional helicopters, rotor transmissions and more. As a consequence, nearly steady solutions can only be achieved as asymptotic conditions of stable transient solutions, if no simplifications are to be accepted.

Structural Dynamics Model

The structural dynamics software that is used in the current simulations is the general purpose multibody/multidisciplinary code MBDyn, which is currently available as "freedom software" from the web site `http://www.aero.polimi.it/~mbdyn/`. It has been successfully applied to the simulation of rotorcraft dynamics; particular focus has been dedicated to tiltrotor aircraft systems, including the 1/5 scale V-22 wind tunnel model known as WRATS, and its recent adaptation to soft-inplane investigations [7, 11], the ERICA tiltrotor concept developed by Agusta S.p.A., now AgustaWestland, and the ADYN wind tunnel model of the European Tiltrotor Concept, which is scheduled for experimental whirl-flutter investigation in late 2005/early 2006. Figure 3 shows a multibody model of the WRATS, where the structural dynamics, the hydraulic control system and basic aerodynamic forces were modeled.

The MBDyn code is a complete multibody analysis tool, particularly suited for rotorcraft dynamics modeling because it features geometrically exact beam models, essential for rotor blade modeling, including composite beam analysis. In fact, the multibody formalism provides arbitrary topology modeling capabilities, included multi-path kinematic chains, and a correct representation of the nonlinear behavior of mechanisms. Within this framework, one can progress from rigid body models, for preliminary performance definition, up to fully detailed aeroservoelastic analysis models, through intermediate steps encompassing detailed mechanism definition, the introduction of deformable elements, servohydraulic actuators, and control systems components. As a consequence, this approach naturally leads to the generation of "modular models" that concur in creating a complete system with the required details for each subpart.

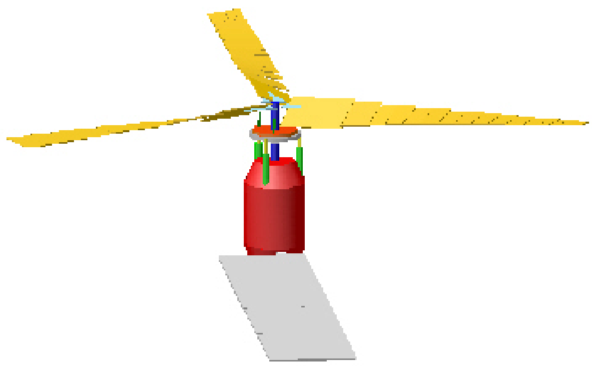


Figure 3: MBDyn model of a tiltrotor system.

Free-Wake Model

The free wake method, which is widely used in the rotorcraft community, derives its appeal from the possibility to solve the whole flow field by representing only the regions where vortical singularities arise.

Table I: Communication patterns

Connector	Input	Output	Notes
Structural Dynamics	loads	configuration	simulation driver
Structural Dynamics	configuration	loads	driven simulation
Fluid Dynamics	configuration	loads	driven simulation
`/dev/null`	loads	none	"rigid" simulation driver; visualization
`/dev/null`	configuration	none	no loads; visualization

To compute an unsteady, time dependent, incompressible flow, Laplace's equation, $\nabla^2\phi = 0$, must be solved in the multiply connected region outside the vortical layers Ω. This equation by itself does not depend on time, but it must be solved together with the appropriate boundary conditions, which prescribe the no-penetration condition on material surfaces

$$(\boldsymbol{\nabla}\phi(\mathbf{x},t) - \mathbf{v}_B(\mathbf{x},t)) \cdot \mathbf{n}(\mathbf{x},t) = 0, \tag{1}$$

where $\mathbf{v}_B$ is the local body velocity and $\mathbf{n}$ is local surface normal. Equation $\nabla^2\phi = 0$ can be solved in the potential variable using Green's classical theorem for harmonic fields (see Morino [12])

$$\phi(\mathbf{x}) = \frac{1}{E(\mathbf{x})} \oint_{\delta\Omega} \left(\phi \frac{\partial}{\partial n}\left(\frac{1}{4\pi r}\right) - \frac{1}{4\pi r}\frac{\partial \phi}{\partial n} \right) dA(\mathbf{x}') \tag{2}$$

where $r = |\mathbf{x} - \mathbf{x}'|$, and $E(\mathbf{x})$ is an operator which is equal to 1,$1/2$ or 0, respectively if $\mathbf{x}$ is positioned inside, on the boundary or outside Ω.

Vortical layers, such as the wake, are surfaces of discontinuity for the kinetic potential. However, they are also stream surfaces, meaning that they are always tangential to the local velocity vector, so

$$(\mathbf{v}-\mathbf{v}_{VL})\cdot\mathbf{n}_{VL} = \Delta(\boldsymbol{\nabla}\phi)\cdot\mathbf{n}_{VL} = \Delta\left(\frac{\partial\phi}{\partial n}\right)_{VL} = 0. \tag{3}$$

where the velocity of the vortical layer is $\mathbf{v}_{VL} = (\mathbf{v}_l + \mathbf{v}_u)/2$, with the subscripts l and u to indicate the two sides of the wake. This last condition means that for vortical layers the second term of Eq. (2) is equal to zero.

Lifting bodies can be usually represented by their mean surface, ignoring the effects of the thickness in the approximate model. This choice is reasonable for thin surfaces, such as typical wings. In this case, both the wake and the body are vortical layers, so any term associated to the discontinuity of the normal derivative of the potential may be dropped.

The velocity field can be reconstructed by considering the gradient of the potential

$$\mathbf{v}(\mathbf{x},t) = \boldsymbol{\nabla}_{\mathbf{x}}\phi = \frac{1}{4\pi}\int_{S_B} \Delta\phi \boldsymbol{\nabla}_{\mathbf{x}}\left(\boldsymbol{\nabla}_{\mathbf{x}'}\left(\frac{1}{r}\right)\cdot\mathbf{n}\right) dA(\mathbf{x}') + \frac{1}{4\pi}\int_{S_W} \Delta\phi \boldsymbol{\nabla}_{\mathbf{x}}\left(\boldsymbol{\nabla}_{\mathbf{x}'}\left(\frac{1}{r}\right)\cdot\mathbf{n}\right) dA(\mathbf{x}') \tag{4}$$

In the virtual singularities theory, the terms associated to a discontinuity in the potential field, called doublets, are mainly responsible for the rise of lifting forces, while the terms associated with the normal derivative of the potential, called sources, are responsible of the effect of the thickness. Because of the equivalence between doublets and vorticity distributions, the same result of Eq. (4) can be obtained using the Biot-Savart law

$$\mathbf{v}(\mathbf{x}) = -\frac{1}{4\pi}\int \frac{(\mathbf{x}-\mathbf{x}')\times\boldsymbol{\omega}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|^3}\, d\mathbf{x}'. \tag{5}$$

A constant distribution of doublets over a flat surface is completely equivalent to a closed loop of straight vortices lying on its perimeter, with constant circulation $\Gamma^L = \Delta\phi$ (see Konstadinopoulos et al. [13]). Using closed loop vortices guarantees the satisfaction of the divergence-free condition for the vorticity. The unknown circulations of the bound vortex lattice which represents the lifting surface may be obtained by applying the boundary condition Eq. (1). As a consequence, the loop circulation on the lifting surface panels is related to the velocity of the fluid at the control points on the boundary. The vorticity generated on the blade is simply convected in the flow field starting from the originating points, which are represented by the trailing edge of the lifting surface. What is needed is a condition to obtain the initial value of the vorticity. The Kutta condition states that the pressure jump between the top and the bottom surface at the trailing edge must be equal to zero. This implies what is known as the Joukowsky hypothesis of smooth flow at the trailing edge, which simply states that the vorticity convected into the flow field is equal to the jump of potential at the trailing edge (see Morino and Bernardini [14]).

The capability of these types of codes to correctly represent the vorticity in the flow field without requiring extremely fine grids, makes them good candidates for the representation of the wake dynamics even when compressibility effects are present in the flow field. In fact, even when large Mach numbers (close to 1) are considered, the asymptotic behavior of vortical wakes is essentially incompressible, as confirmed by experimental results, see Gai et al. [15]. This happens because the wake dynamics is governed by the Mach number related to the relative velocity, which is often very low since the wake elements are stationary or move slowly compared to the sound celerity.

The free-wake analysis software that is used in the current simulations is called NUVOLA [16]. It features a nonlinear unsteady incompressible vortex lattice method, capable to predict the instantaneous configuration of the wake and the distribution of the aerodynamic loads on flexible rotor blades during arbitrary unsteady flight conditions.

The aerodynamic loads computation is based on the use of Bernoulli's theorem

$$\frac{\partial \phi(\mathbf{x})}{\partial t} + \frac{v(\mathbf{x})^2}{2} + \frac{p(\mathbf{x})}{\rho} = \frac{v_\infty^2}{2} + \frac{p_\infty}{\rho}. \qquad (6)$$

By means of simple mathematical elaborations the pressure jump across each surface panel appears to be made of two contributions: one related to the velocity potential jump in the local reference frame, and thus equal to the time derivative of the loop circulation; the other, which can be referred to as the stationary part, related to the vorticity value can be computed using the classical Kutta-Joukowsky formula which states that a vortical flow generates a load $\mathbf{F} = \rho \mathbf{v} \times \mathbf{\Gamma}$. The separate computation of these contributions gives the opportunity to improve the aerodynamic loads evaluation since the Kutta-Joukowsky formula can be applied to a more refined set of points. A better representation of the leading edge suction can be obtained using the Kutta-Joucowsky theorem together with the unsteady contribution. This effect, typical of relatively thick airfoils, is important since it may considerably affect the induced drag.

Fluid-Structure Interface

To solve a coupled fluid structure problem, the capability to compute the solution of the structural and of the aerodynamic model is not sufficient. It is also necessary to exchange information between the two models: the modification of the boundary conditions must be transferred from the deformable structure to the aerodynamic boundary, and conversely, the loads resulting from the aerodynamic field must be applied to the discretized structural model. The adoption of two different codes for the simulation of the two physical domains gives the possibility to (or raises the problem of) dealing with "non-compatible" discretizations, e.g. beam elements for the structure and flat lifting surfaces for the aerodynamics (see Figure 4); the exchange layer must connect entities which may be extremely different from a topological point of view.

The field interpolation is a key task, which is accomplished by the broker. An accurate method, capable of interfacing any possible structural or aerodynamic discretization scheme, is required. The basic technique is inferred from surface reconstruction theory, which deals with reconstructing regular surfaces from scattered data. As opposed to what has been presented by Farhat et al. [17], a complete independence from the formulation of the structural system is achieved with the proposed technique, while retaining the required conservation properties.

The fluid boundary movement is indicated by $\mathbf{y}_f$; $\mathbf{y}_s$ denotes the structural boundary movement; p the pressure acting on it, σ_s and σ_f respectively the structure stress tensor and the fluid viscous stress tensor, and $\mathbf{n}$ the normal vector to the interface boundary Γ. The compatibility conditions are

$$\left.\begin{aligned} \sigma_s \cdot \mathbf{n} &= -p\,\mathbf{n} + \sigma_f \cdot \mathbf{n} \\ \mathbf{y}_s &= \mathbf{y}_f \\ \dot{\mathbf{y}}_s &= \dot{\mathbf{y}}_f \end{aligned}\right\} \quad \text{on } \Gamma. \qquad (7)$$

The first of Eqs. (7) expresses the dynamic equilibrium between the stresses on the structure and those on the fluid side. The other two are kinematic compatibility conditions. The last one, for inviscid flows, is replaced by a condition only on the normal component of the velocity

$$\frac{\partial \dot{\mathbf{y}}_s}{\partial n} = \frac{\partial \dot{\mathbf{y}}_f}{\partial n}.$$

These conditions are valid regardless of the formulation used for the description of each field; the aerodynamics can be approximated either by the Euler equations or any other CFD model, or even by a simple panel method.

Eqs. (7) are valid for a continuous system. However, the two fields are solved resorting to a discrete approximation based on finite approximations of the functional space under which the solutions fall. As a consequence, the correct expression of Eqs. (7) for the discretized problem must be derived, under the constraint of retaining the conservation properties of the original problem, see van Brummelen et al. [18]. The mass conservation is trivially satisfied since there

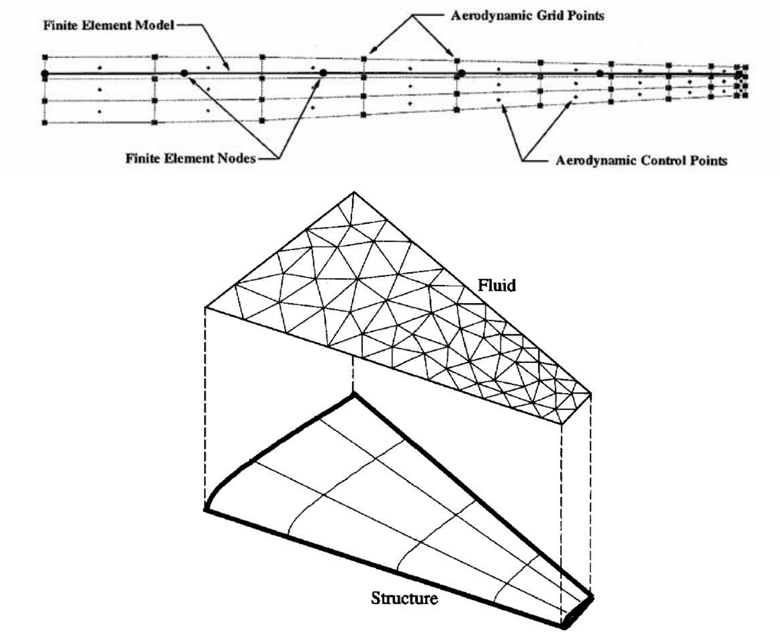


Figure 4: Possible fluid-structure interfaces.

is no mass exchange. The change of energy in the fluid-structure system equals the energy supplied (or absorbed) by an external force. Consequently, at any time t, the energy released/absorbed from the structure, except for the contribution dissipated by the structural damping, must balance the energy absorbed/released by the fluid, or, in other words, the work equivalence must hold. Finally, the change of momentum of the fluid-structure system may be induced only by external forces.

The conservation properties are retained when the two computational domains of the fluid and structure have matching discrete interfaces and compatible approximation spaces, such as identical spaces for the stresses at either side of the interface. However, in realistic applications, the fluid and structural meshes are not compatible along the interface, either because discretized with major geometric discrepancies, or because each problem has different resolution requirements; typically, the fluid grid, at the interface, is finer than the structural mesh. In the following, Γ_f and Γ_s will respectively indicate the discrete fluid/structure non-matching representation of Γ.

In order to satisfy the conservation between the two models, the correct strategy would be to enforce the coupling conditions only in a weak sense, through the use of simple variational principles such as the Virtual Works one. Let $\delta\mathbf{y}_f$ and $\delta\mathbf{y}_s$ be two admissible virtual displacements for each field. Admissible means that the trace of these two fields on Γ must be equal.

Regardless of the interpolation method chosen to enforce the compatibility of the displacements, the relationship between the admissible virtual displacements can be written as

$$(\delta\mathbf{y}_f)_i = \sum_{j=1}^{j_s} h_{ij}\,(\delta\mathbf{y}_s)_j, \tag{8}$$

where $(\delta\mathbf{y}_f)_i$ are the discrete values of $\delta\mathbf{y}_f$ at the fluid nodes of the grid on the wet surface, and h_{ij} are the coefficients of the displacements interpolation matrix H. The resulting virtual displacement of the boundary surface will be

$$\delta\mathbf{y}_f = \sum_{i=1}^{i_f} N_i \sum_{j=1}^{j_s} h_{ij}\,(\delta\mathbf{y}_s)_j. \tag{9}$$

Shape functions N_i belong to the approximation space of the aerodynamic field discretization, and i_f is the number of nodes which belong to the interface surface Γ_f. The virtual work of the aerodynamic load is equal to

$$\begin{aligned}\delta W_f &= \int_{\Gamma_f} (-p\,\mathbf{n} + \sigma_f \cdot \mathbf{n}) \cdot \delta\mathbf{y}_f\, d\mathbf{A},\\ &= \int_{\Gamma_f} (-p\,\mathbf{n} + \sigma_f \cdot \mathbf{n}) \cdot \sum_{i=1}^{i_f} N_i \sum_{j=1}^{j_s} h_{ij}\,(\delta\mathbf{y}_s)_j\, d\mathbf{A}.\end{aligned} \tag{10}$$

On the other side, the virtual work of forces and moments acting on Γ_s is equal to

$$\delta W_s = \sum_{j=1}^{j_s} \mathbf{f}_j \cdot (\delta \mathbf{y}_s)_j. \tag{11}$$

Imposing the equality of the virtual works and calling $\mathbf{F}_i$ the quantity given by

$$\mathbf{F}_i = \int_{\Gamma_f} (-p\,\mathbf{n} + \sigma_f \cdot \mathbf{n}) N_i \, d\mathbf{A}, \tag{12}$$

the nodal loads applied to the structure are

$$\mathbf{f}_j = \sum_{i=1}^{i_f} \mathbf{F}_i \, h_{ij}. \tag{13}$$

Eq. (13) states that, after computing the nodal loads for the aerodynamic boundary grid points using the correct approximation space, $\mathbf{F}_i$, the loads on the structural nodes, $\mathbf{f}_j$, can be obtained by simply multiplying $\mathbf{F}_i$ for the transpose of the interpolation matrix H computed to connect the two grid displacements. The conservation problem is now shifted on the definition of the appropriate interpolation matrix H.

To build a conservative interpolation matrix which enforces the compatibility, Eq. (7), a weak/variational formulation can be used as well. The problem can be expressed in weighted least square form

$$\text{Minimize } \int_{\Gamma} \phi \left(\mathrm{Tr}\,(\delta \mathbf{y}_f)|_{\Gamma} - \mathrm{Tr}\,(\delta \mathbf{y}_s)|_{\Gamma}\right)^2 d\mathbf{A} \tag{14}$$

where $\mathrm{Tr}\,(\cdot)$ is the trace operator. Additional properties like smoothness of the resulting field after interpolation, computational efficiency, and some control on the interpolation error, can be sought for. A solution which possesses all these qualities can be obtained using the Moving Least Square (MLS) technique; recently, this type of approximation attracted the researchers' attention also for meshless methods for the numerical solution of PDEs, see Belytschko et al. [19]. After calling $f(\mathbf{x})$ the function which represents the $\mathrm{Tr}\,(()\,\delta \mathbf{y}_s)$, the first step is to build a local approximation of f as a sum of monomial basis functions $p_i(\mathbf{x})$

$$\hat{f} = \sum_{i=1}^{m} p_i(\mathbf{x}) a_i(\mathbf{x}) \equiv \mathbf{p}^T(x)\,\mathbf{a}(x), \tag{15}$$

where m in the number of basis functions, and $a_i(\mathbf{x})$ are their coefficients, which are obtained by a weighted least square fit for the approximation

$$\begin{aligned} &\min_{\mathbf{x}} J(\mathbf{x}) = \\ &\min_{\mathbf{x}} \int_{\Omega} \phi(\mathbf{x} - \bar{\mathbf{x}}) \left(\hat{f} - f(\bar{\mathbf{x}})\right)^2 \, d\Omega(\bar{\mathbf{x}}) \end{aligned} \tag{16}$$

under the linear constraint

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{m} p_i(\bar{\mathbf{x}}) a_i(\mathbf{x}). \tag{17}$$

This equation is completely equivalent to Eq. (14) which expresses the interface problem (all the details may be found in [20]). The problem is localized by choosing weight functions that are smooth non-negative Radial Basis Function (RBF) with compact support [21]. The adoption of different RBF functions, together with the definition of the local support dimension, allows to achieve the required regularity of the interpolated function.

The resulting interface matrix satisfies all the requirements. It is effective, because the major computational complexity, which lies in the geometric part of the computation, can be accomplished in an efficient manner; it can produce surfaces with any prescribed smoothness; it allows a high control on the behavior for each local region. The interface method is completely independent from the implementation details of the codes that are interfaced. There is no need to know what shape functions are used for each field; as a consequence, the implementation of the structural elements or the code used to solve the aerodynamic field can be changed without affecting the interface code.

The last problem that requires special attention is related to the treatment of rotations, since we are dealing with structures that can experience large changes in orientation. Rotations need to be accounted for, e.g., when a beam structural model is interfaced to an aerodynamic surface boundary. Rotations are complex tensorial entities that can be subjected to singularity problems when parameterized. To avoid the need to build a specialized class of interpolation matrices for these entities, since the updated position of an aerodynamic surface node is obtained by combining the effect of linear displacements and rotations, a simple procedure has been developed. The idea is to add three rigid arms to each structural beam node, directed along the node local reference axes, creating a sort of "fish-bone" structure. The effect of the rotation is accounted for by the displacements of the added dummy nodes at the end of each arm, and the matrix H is computed using displacements only.

As an example (more can be found in [20]) the behavior of the interface is analyzed for a simple straight, unswept helicopter blade with a NACA 0012 airfoil and an aspect ratio of 10. This choice is intended to show the interfacing capabilities of the proposed scheme when the underlying structure is represented by means of beams. The structural model is made of five beam elements, while the aerodynamic sur-

Table II: Helicopter blade linear twist: twist angle at station 9 m.

Scheme	Angle	% Error
Analytic	18	0
Linear C^0 10 pts.	17.9886	0.06
Linear C^0 20 pts.	17.2094	4.40
Linear C^4 20 pts.	17.7743	1.25
Quadratic C^4 20 pts.	17.9880	0.06
Quadratic C^4 30 pts.	17.9905	0.05

face is represented by a structured grid of 200×21 nodes. The fish-bone structure is obtained by adding four rigid arms at each node, a couple for each direction perpendicular to the beam axis. The two arms in each direction have opposite sign to obtain a final layout which respects the symmetry. As a result, the rotation of each node is correctly transmitted to the aerodynamic wet surface. For the first test case, a linear twist has been applied along the blade, from 0 deg at the root to 20 deg at the tip. Table II compares the analytical twist angle of the airfoil nodes on the deformed blade at 90% of the blade span, with the corresponding results obtainable with different interfacing schemes.

Coupled Integration

Up to this point we have analyzed all the details concerning the modeling of each field which represents the physics under investigation, or how to exchange information between the different fields. However, when tight interactions between the component fields take place, the response of the overall system must be calculated concurrently. Various strategies can be adopted to solve this problem, with specific pros and cons, depending on the respective implementation. Usually each domain has its peculiarities, which require special numerical strategies to successfully accomplish the integration. At the same time, different space and time scales may arise in each field, so they must be correctly either represented or filtered out in the coupled simulation.

Often, a staggered procedure is used for the coupled simulations, in which separate fluid and structural analysis codes are run in a strictly sequential fashion, and they exchange interface data such as surface stresses and velocities at each time step (Piperno et al. [22] and Zwaan and Prananta [23]). A classical staggered algorithm working cycle is composed by:

a) advance the structural system under the pressure loads computed at the previous step $(\mathbf{x}_s^{n+1}, \dot{\mathbf{x}}_s^{n+1})$;
b) update the fluid domain boundary conditions (and eventually the mesh) $(\mathbf{x}_f^{n+1}, \dot{\mathbf{x}}_f^{n+1})$;
c) compute the new pressure loads p^{n+1}.

In this case at each time step there is no balance between the energy developed by the fluid force on the structure and the energy gained by the fluid on the interface, since

$$\begin{aligned}&\int_{\partial\Omega_B} (p^n \mathbf{n} \cdot \dot{\mathbf{x}}_s^{n+1} - p^{n+1}\mathbf{n} \cdot \dot{\mathbf{x}}_f^{n+1})\, dA = \\ &\int_{\partial\Omega_B} (p^n - p^{n+1})\mathbf{n} \cdot \dot{\mathbf{x}}_s^{n+1}\, dA \neq 0\end{aligned} \tag{18}$$

As a result, using unconditionally stable time integration algorithms in each field analyzer does not guarantee the unconditional stability of the overall staggered solution algorithm. These schemes may become energy increasing and, hence, numerically unstable. To enlarge the stability boundaries, preserving at the same time the modularity that characterizes the partitioned methods, a new class of methods which can be called "fully implicit partitioned methods". For the solution of the fluid-structure interaction problem under investigation, an implicit partitioned method has been chosen, based on a relaxation technique similar to the one presented by Le Tallec and Mouro [24], which has two advantages:

A) it can be easily integrated with the solution algorithm currently implemented for the multibody code;
B) by using the relaxation factor, the method can be adapted to different operative conditions.

The algorithm at each time step performs the following operations

1) guess the position and velocity of the structural elements by using the explicit second-order predictor of MBDyn [25];
2) obtain the position and velocity of the fluid boundary elements using the conservative scheme here presented;
3) solve the fluid problem;
4) compute the interface loads;
5) transform the loads computed at the previous point into nodal forces using the correct approximation space, which is the constant function space for pressures on panels and forces per unit length on lines;
6) evaluate the residual of the nonlinear structural problem applying the aerodynamic loads computed by the interface process and check for convergence: if the algorithm has converged stop the cycle;

7) solve the structural problem;
8) update the structural interface position according to the relaxation equation

$$\mathbf{x}_s^{n+1} = (1-\omega)\mathbf{x}_s^n + \omega \mathbf{x}_s^{n+1}; \qquad (19)$$

9) go back to step (2).

Le Tallec and Mouro [24] have shown that this type of scheme is equivalent to a preconditioned descent algorithm for which the stability of the method with $\omega = 1$ is threatened when the parameter $K_{ref}\Delta t^2$ is small, where K_{ref} is a characteristic stiffness of the problem under investigation. This means that the iterative scheme may encounter convergence problems when dealing with soft structures or small time steps. For these cases, under-relaxation may be used.

Often, the displacements of the structural nodes during the correction phase are small. In these cases it is convenient, in terms of computational time savings, to avoid updating the velocity that is induced at each panel by the wake vortices. By simply projecting the induced velocity computed during the prediction phase along the new normal direction of each panel, large time savings can be achieved with a very small error. This error can be estimated, by looking at the Biot-Savart formula, Eq. (5), as proportional to $O(\delta r/r^3)$, where δr is the position variation of the control node of the panel.

Applications

Validation: Caradonna-Tung Rotor

The experimental results of Caradonna and Tung [26] are typically chosen as validation test for helicopter aerodynamic codes. In this case the rotor blades are rigid, so no deformability is involved; however, the test is useful to asses how the coupled procedure, which involves the multibody code, the broker and the free wake code, behaves. The test here addressed for validation purposes was run with 8 deg of collective pitch at 1250 rpm; the tip Mach number was 0.439, so the flow field can be considered incompressible. Higher Mach numbers will be tested after the integration with CFD codes is completed. The rotor is in hover, and no initial wake is assigned, so the system must reach the regime condition after developing is own wake from the wind-up. For the hover simulation with time marching algorithms, the initial wake state is critical because the the wake can become unstable owing to strong starting vortices generated by the impulsively starting blades. The problem can become unstable especially for the vortex released by the inner extremity of the blade at the root cut-out. In fact, the start-up vortex at the inner root creates a vortex ring with a small radius, which rapidly becomes unstable and causes the rise of an upward flow in the inner disk around the hub; an example of this wake phenomenon is shown in Figure 5. After the start-up phase, the inflow velocity induced by the developing wake is capable of pulling the new wake elements downward in the external region, but not in the inner region, where a fountain effect appears. This effect may cause a global instability of the wake, as shown in Figure 6 for the time history of the traction coefficient C_T which corresponds to the wake of Figure 5. In the present work, different methods, which do no require an initial solution for the wake and are at the same time computationally efficient, have been tested. A stable and correct solution may be obtained by simply imposing a very fast growing law for the core radius of

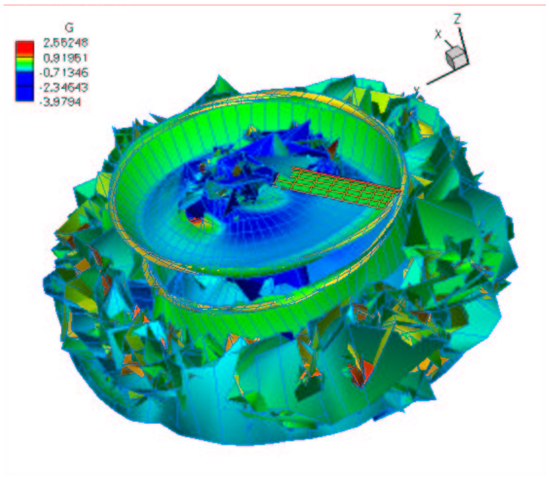


Figure 5: Wake developed by Caradonna-Tung rotor: instability of the inner vortex ring.

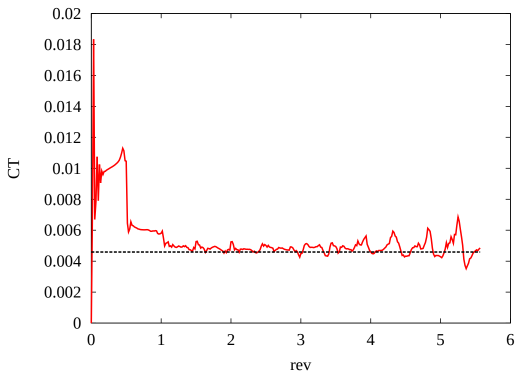


Figure 6: Traction coefficient for Caradonna-Tung unstable solution; the dashed line represents the experimental value.

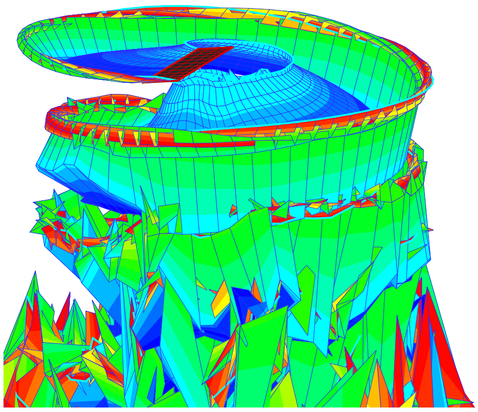


Figure 7: Wake developed by Caradonna-Tung rotor: stable algorithm.

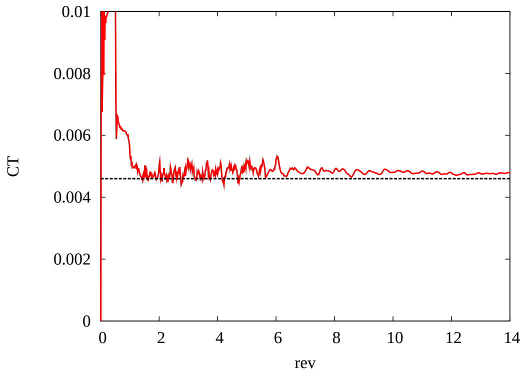


Figure 8: Traction coefficient for Caradonna-Tung rotor stable solution; the dashed line represents the experimental value.

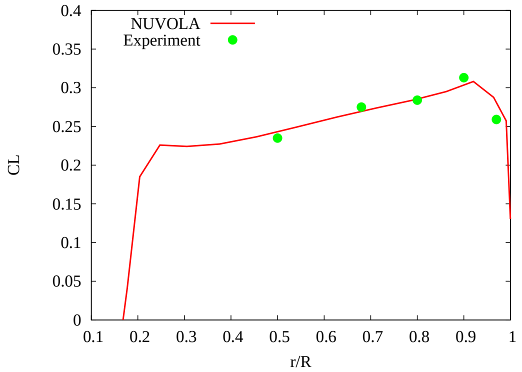


Figure 9: Caradonna-Tung rotor: section lift coefficient.

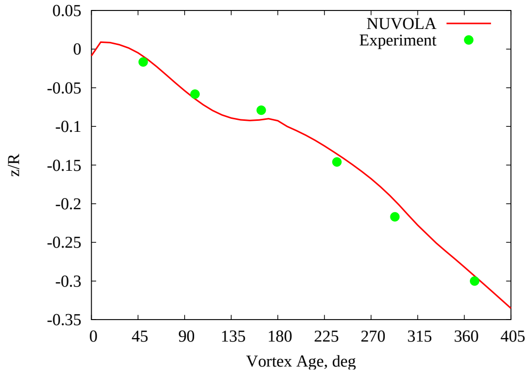


Figure 10: Caradonna-Tung rotor: position of the tip vortex.

the start-up and the inner vortex, somehow simulating the vorticity diffusion which acts in the real experiment. The solution obtained in this case is shown in Figure 7, with the corresponding traction coefficient in Figure 8. Figure 9 shows the good correlation in terms of spanwise section lift coefficient, while Figure 10 shows the good correlation in terms of vortex vertical position as function of the azimuth.

Puma Rotor in Forward Flight

A full scale articulated helicopter rotor has been considered as the final test. The Aerospatiale AS 330 Puma helicopter aerodynamic behavior was investigated during the end of the '80s by different worldwide research agencies to assess the accuracy of comprehensive analysis codes and CFD Full Potential methods for the prediction of airloads on a helicopter blade in high-speed flight. All the experimental and numerical results obtained, together with a detailed report of the aircraft configuration can be found in Bousman et al. [27].

This test case has been chosen here in order to obtain detailed numerical results that can be compared with experimental data. An articulated rotor represents a very interesting case for Fluid Structure Interaction (FSI) coupled analysis, since large displacements due to rotations about the hub hinges may take place, essentialy governed by the aerodynamic hinge moments. Furthermore, the high-speed tests represent an interesting base for comparison with the CFD techniques that will be developed in the following.

As a first assessment, rigid blades have been considered. The results obtained by the FSI procedure are compared with what can be obtained by a simple blade section method with uniform inflow. At this stage, the tests have been mainly considered a way to assess the correctness and the ffectiveness of the FSI procedure. Future tests will address the modeling of flexible blades, comparisons with the experi-

Table III: Puma flight 123 parameters.

Advance ratio, μ	0.321
Shaft angle of Attack, α_s	-6.0
Collective pitch, θ_c	13.2
Fore-aft cyclic pitch, θ_{fa}	-7.15
Lateral cyclic pitch, θ_l	2.1

mental results available so far, and the coupled integration with CFD techniques. The baseline forward flight case made with the standard unswept blade, Flight Test 123 (see [27]) has been selected for the initial computations. The rotor configuration data has been extracted from the report [27]. More information about the helicopter global characteristics may be found in [28]. The rotor model is made of four articulated blades. The multibody model of the hub includes:

- a complete, kinematically exact model of the swashplate;
- all the blade hinges;
- a rigid pitch link is used, because the report does not contain enough information on the control system stiffness;
- a viscous damper acting about the lead-lag hinge;
- the rigid blades.

The flight condition parameters are presented in Table III. The rotor control angles were computed by trimming the simple (blade section aerodynamics + uniform inflow) model. The coupled model has been run imposing the controls computed from the simpler model without looking for a specific trim condition.

A coarse grid on each blade, made by 5 elements along the chord and 10 along the span, has been used together with a coarse time discretization, since only 45 time steps for each rotor turn were used. This means that the results presented in the following are only a first assessment of the capabilities of the algorithm. More tests with a finer grid, together with a flexible blade model need to be conducted before making a comparison with flight test measurements. However, note that the rotor is fully articulated and the motion of the hinges is not imposed; on the contrary, it results from the equilibrium, so the test can be considered significant for the assessment of the stability and robustness of the interaction procedure. For this case, the rotor wake has been "forgotten" after three rotor turns, without significantly affecting the velocity induced by the wake on the rotor disk. Figure 11.

The overall Z force generated with the vortex lattice model is slightly lower than that resulting from the inflow models. Looking at the load distributions obtained by the two models, Figure 12, the main differences for the vortex lattice model are slightly higher loads in the inner part of the blade, and lower loads near the tip due to the tip loss effects, which are not correctly accounted for in the simpler model.

Toward CFD Fluid-Structure Interaction

The element that characterizes the rotorcraft fluid flows and makes their modeling so difficult is the wake. The interaction between blades and vortices, expecially at low rotorcraft speed, gives rise to major important phenomena, such as vibratory loads and BVI noise. At the same time, at high forward speed, compressibility phenomena need to be accounted for. The previous sections showed how the use of a vortex method allows to simulate the dynamics of the rotor wake. However, this type of approach suffers from two limitations:

A) the aerodynamic field is considered incompressible;

B) the local interaction between vortices and solid boundaries cannot be easily represented.

On the CFD side, the integration of the free wake model for generic deformable blades represents a first step toward the complete aeroelastic analysis of helicopter rotors and tiltrotors. In fact, accrding to the driving principle of applying the most appropriate physical model for each fields or sub-field, the free-wake model can be used to compute the "far-blade" sub-field (or "far-wing" for tiltrotors), where the correct approximation of the vorticity is the main goal, while CFD based on Euler or Navier-Stokes equations should be used in the "near-blade" sub-field to correctly account for compressibility effects and interactions with solid boundaries. It will be easy to add a CFD code in the framework here presented using the broker as the interface and interaction coordinator between the different pieces of codes that will concur in the simulation.

Conclusions and Future Work

This paper illustrates the application of a computational framework for the simultaneous solution of multi-field initial value problems to the coupling of a free-wake modeling software to a multibody/multidisciplinary analysis software. A novel approach to solution coupling is presented, based on a communication synchronization and field interpolation process called "broker". This is expected to show a minimal impact on the participating analysis

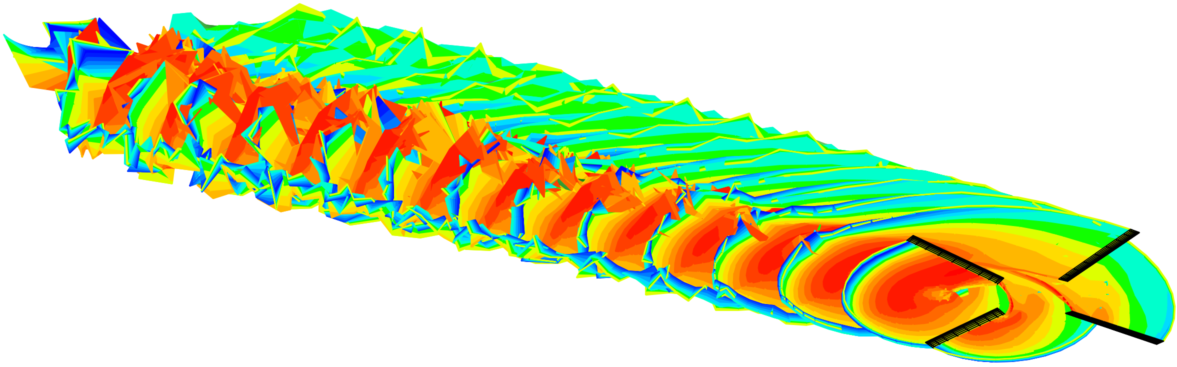
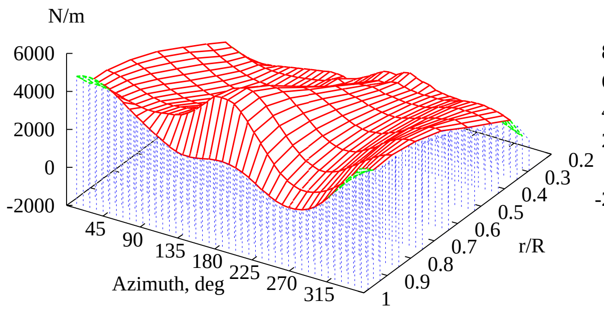
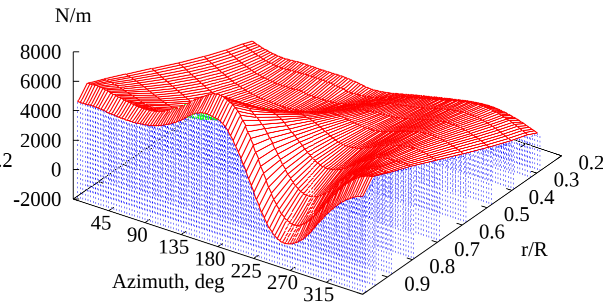


Figure 11: Puma rotor in forward flight: vorticity over the wake.



a) Vortex lattice



(b) Blade section + inflow

Figure 12: Puma forward flight: rotor Z sectional force distribution.

software, and in most cases it should allow their use without even minor changes, which may be a mandatory requirement in case the source code is not available. Different communication patterns are available to allow the broadest applicability of the scheme. The framework has been applied to the integrated solution of aeroelastic problems, and is being applied to rotorcraft dynamics analysis.

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