XVI CONGRESSO NAZIONALE AIDAA
24–28 settembre 2001
PALERMO

EXPERIENCES OF MULTIBODY MULTIDISCIPLINARY ROTORCRAFT ANALYSIS

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ABSTRACT

The experiences on multibody multidisciplinary analysis of rotorcraft made over the years by a research group at the Department of Aerospace Engineering of the University "Politecnico di Milano" are presented. The original formulation that has been developed and implemented is briefly presented; different applications are discussed, emphasizing the multidisciplinary aspects of the work.

1. INTRODUCTION

The multibody approach to the integrated analysis of sophisticated systems is gaining acceptance in the aerospace engineering as a very important analysis tool because it allows to model very complex problems in a general manner, without requiring most of the oversimplifying assumptions usually considered by dedicated solution approaches. Although the dynamics and the stability of conventional fixed-wing aircraft are not likely to take any advantage from a multibody approach, aircraft landing and taxiing, aircraft crash and impacts, space structure deploying and rotorcraft dynamics are research fields that undoubtedly can take the major advantages from the power of the multibody analysis. The Department of Aerospace Engineering of the University "Politecnico di Milano" has been active in the field of rotorcraft dynamics analysis since the mid seventies. Figure 1 shows a pictorial representation of the chronology of multibody analysis at our Department. Different research groups have been investigating the multibody approach applied to different aspects of the problem, ranging from aircraft and helicopter crash, impact

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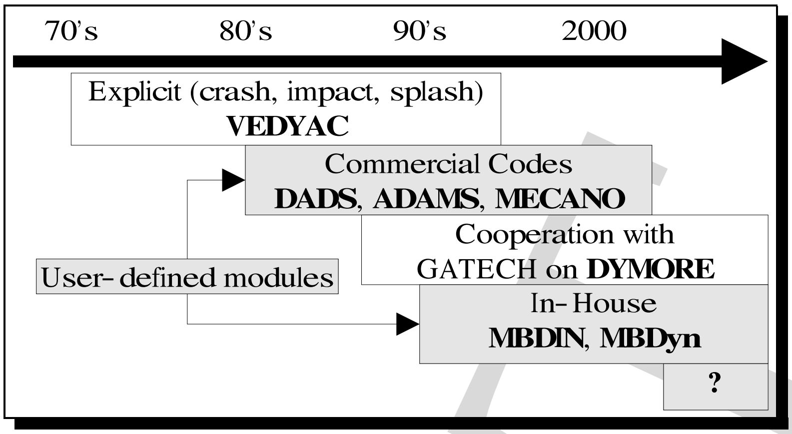

Figure 1: Chronology of multibody analysis at the Department of Aerospace Engineering of the University "Politecnico di Milano"

and airworthiness assessment, to aircraft landing and ground roll loads analysis, to rotorcraft dynamics and aeroservoelasticity. The first attempts were focused on explicit codes, which were developed to investigate the fast dynamics that occur during aerospace and automotive impacts. The resulting multibody code, VEDYAC, is still in use and evolving to adapt to new needs in airworthiness investigation. While other researchers were mainly focusing on algorithmic implications and on computational mechanics in a broader sense, eventually resulting in cooperations with international partners, our research group felt the need to acquire the internal capability to analyze the aeroservoelasticity of rotorcraft. As a result, an original formulation has been developed starting in the late eighties, and has been subsequently extended to account for multidisciplinary problems such as those related to the active control of the system. At the same time, the formulation has been implemented in a general-purpose multibody analysis code called MBDyn. Recently, the modeling of general-purpose degrees of freedom and elements has been added to allow the investigation of active control problems. Smart components, adaptive controllers, different sensors and actuators have been considered; the comprehensive modeling of hydraulic components represents the last developed application. The orientation towards multidisciplinary analysis has been kept in mind from the beginning in designing the code, resulting in easy extension to new aspects of the integrated analysis. On the computational side, a very effective coarse-scale parallelization of the solution based on domain partitioning allowed a substantial speedup when solving comparatively large models ($10^3 \div 10^4$ DOFs). The model preparation and data reduction phases become a challenge as the size and the complexity of the model and of the problem increase. To avoid the overhead of implementing a dedicated pre/post processing interface, the code is being interfaced to MDI's ADAMS/Wiew.

2. MULTIBODY DYNAMICS

The problem of analyzing the dynamics of a aeroelastic system is stated by writing the constrained dynamics of a set of rigid bodies in terms of equilibrium equations, where the inertia is accounted for by defining the momentum and the momenta moments in terms

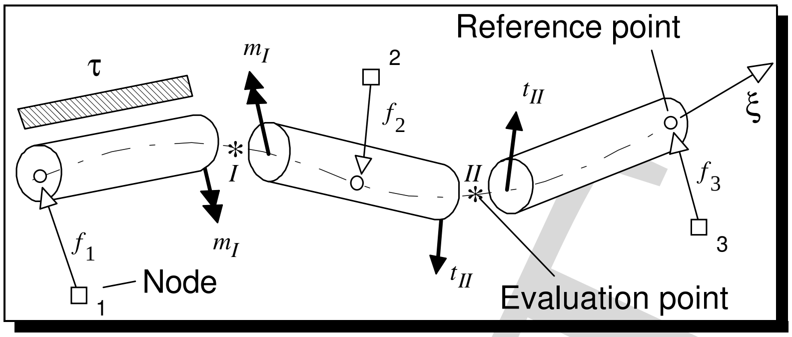

Figure 2: Finite volume beam element sketch.

of the kinematics of the bodies:

$$\begin{aligned} \beta &= m\dot{x} + \omega \times S \\ \gamma &= S \times \dot{x} + J\omega \end{aligned} \tag{1}$$

The implicit differential equilibrium equations are

$$\begin{aligned} \dot{\beta} &= F\left(x, R, \omega, a, \ldots, t\right) \\ \dot{\gamma} + x \times \beta &= C\left(x, R, \omega, a, \ldots, t\right) \end{aligned}$$

where the external forces F and couples C may depend on the configuration (elasticity, aeroelasticity) and on internal states a (constraint reactions, coupled fields e.g. hydraulics). The problem is constrained by adding algebraic equations

$$\Phi\left(x, R, \ldots, t\right) = 0$$

that introduce holonomic and non-holonomic constraints, thus resulting in an index 3 Differential/Algebraic System. Reaction unknowns result, that apply to the equilibrium equations:

$$\begin{aligned} \dot{\beta} &= F\left(x, R, \omega, a, \ldots, t\right) + V_F \\ \dot{\gamma} + x \times \beta &= C\left(x, R, \omega, a, \ldots, t\right) + V_C \end{aligned}$$

These problems require an unconditionally stable, implicit integration scheme to overcome the algorithmic stability problems posed by the algebraic part. A very effective multistep second-order accurate formula with tunable algorithmic dissipation has been internally developed [1]. Elasticity is mainly modeled by means of finite volume beam elements [2], Figure 2, although modal flexibility is also available.

3. IMPLEMENTATION

The code was originally implemented in Fortran 77. An original multistep implicit integration algorithm was used to directly integrate the dynamics of mixed first- and second-order differential/algebraic equations in a general manner. Starting in 1996, it has been entirely re-engineered using an Object-Oriented programming approach in C++. Many important modules maintained the original F77 implementation, including the linear algebra

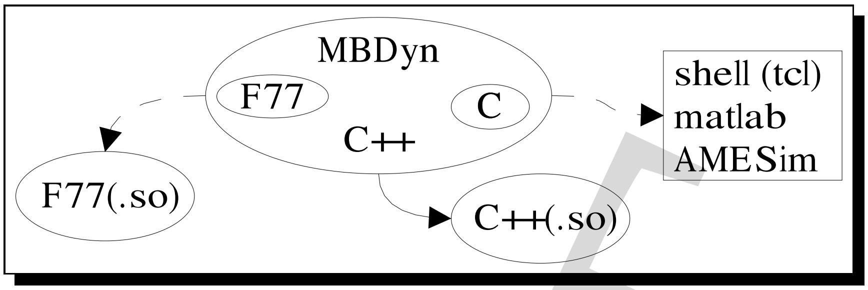

Figure 3: Architecture of the program. The `.so` parts refer to dynamically loadable modules. The interfaced external programs are also depicted.

```
double m;
Vec3<double> Beta, Gamma, DotX, Omega, S;
Mat3x3<double> J;
// ...
Beta = DotX*m + Omega.Cross(S);
Gamma = S.Cross(DotX) + J*Omega;
```

Figure 4: C++ coding of Equation 1

solver, the raw aerodynamic forces and some computationally intensive math routines. By adding the equations that represent the definitions of the momenta, the problem has been rewritten in terms of first-order differential/algebraic equations. The multi-language programming approach allowed on one side to preserve a considerable amount of lines of thoroughly tested F77 code, while exploiting many unique features of Object-Orientation, expecially in data structuring, data handling, I/O, and significantly in data abstraction at the problem-coding level. Figure 3 shows the architecture of the code in terms of languages used in coding modules (the `.so` refer to external, dynamically loadable modules) and of interfaces towards external programs. One remarkable example is represented by the introduction of a complete 3×1 vector and 3×3 matrix algebra for the handling of the three-dimensional entities that are typical in multibody analysis, with fully overload math operators. This allowed the coding of many problems in a very neat manner, with limited computational overhead, if any. As an example, the momenta definitions, Eq. 1, are coded in Figure 4.

4. AERODYNAMICS MODELING

The initial implementation of the aerodynamic forces was very simple, based on the strip theory, with interpolation of the aerodynamic coefficients spanning 360 degrees of incidence and yaw correction for lift and radial drag. The rotor inflow is described by models of incresing sophistication, from uniform inflow to *Glauert*'s model to the dynamic inflow scheme. At present, this approach is used for basic performance and stability analysis, and it is considered a good trade-off between the sophistication of a multibody code and the first-approximation needs of performance and stability computations. Loose integration with CFD codes has been considered in the past, by interfacing an internally developed code for uncompressible potential wake modeling, called NUVOLA [3], see Fig-

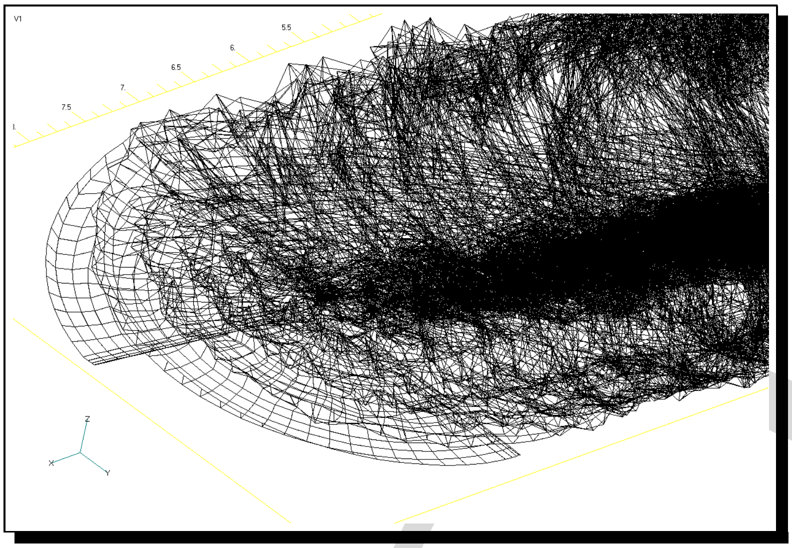

Figure 5: Free wake of a rotor in forward flight.

ure 5. There are plans for further development of such integration, and for more general integration schemes towards different CFD codes.

5. AEROELASTIC TAYLORING

Very interesting results have been obtained in the aeroelastic tayloring of rotor blades. The elastic coupling related to the use of anisotropic composite materials, together with usual inertial coupling, introduce a high degree of complexity in the analysis and design of advanced rotor blades. While many analysis formulations allow to introduce inertial coupling in conventional beam modeling, the use of complete, although realistic elastic coupling is relatively unusual. By using an original beam section characterization formulation [4, 5], and by incorporating it into a multilevel optimization that used the multibody analyses to contribute to the objective function, the aeroelastic tayloring of a rotor blade has been carried out [6]. Figure 6 shows the elastically coupled in-plane mode of the final blade. The mode is compared to the analogous mode that can be obtained by a conventional FEM beam modal analysis, which neglects elastic couplings, and the verification of the mode with a three-dimensional FEM model of the blade.

6. ACTIVE CONTROL

The multidisciplinarity of the initial approach allowed to extend the formulation to the integrated analysis of active control systems with limited effort. Generic high-level elements, such as sensors (e.g. accelerometers, strain gages associated to the beam elements), actuators (variable length constraints, piezo-electric devices applied to the beam elements, as discussed in the following section), and conditioning circuitry (analog filters) have been implemented. A sophisticated adaptive control scheme, such as the *Generalized Predictive Control*, has been implemented. It consists of a discrete-time control that computes the control signal required to bring the predicted behavior of the system to a desired level in

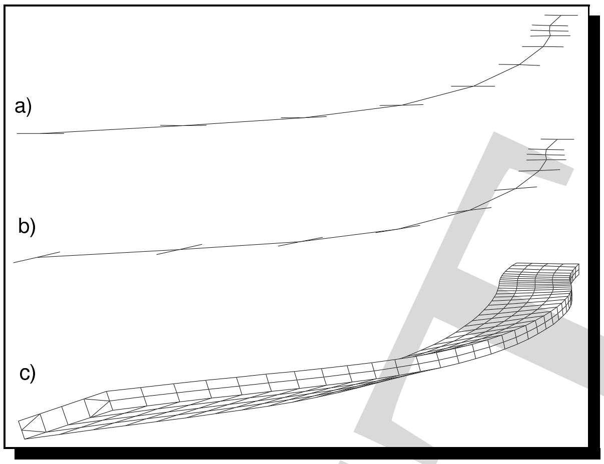

Figure 6: Aeroelastic taylored blade in-plane bending mode: a) uncoupled beam, b) elastically coupled beam, c) 3D FEM verification

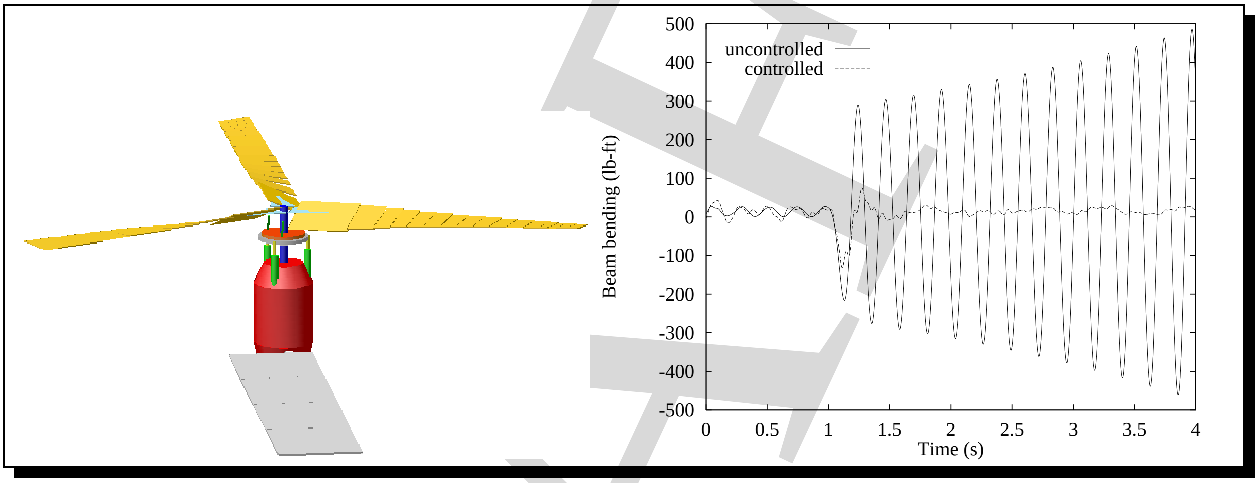

Figure 7: WRATS semispan tiltorotor model; left: sketch; right: wing bending due to a vertical gust close to flutter speed with and without GPC control.

a finite number of steps, based on a discrete-time realization of the system. By continuously identifying the problem, and by cyclically redesigning the controller, an adaptive scheme can be obtained. Its aplication to a a tiltrotor aircraft, aimed at load reduction with some flutter suppression capabilities, has been investigated [7, 1]. The control is performed by controlling the elongation of the three swashplate actuators based on three measures of strains at the wing root and on three measures of accelerations at the pylon. The complete mechanics of the control system are modeled by means of algebraic constraints. Figure 7 shows a screenshot of the WRATS tiltrotor model and the comparison of the wing bending moment due to a vertical gust close to flutter speed with and without GPC control.

7. SMART MATERIALS

As far as the interest in using smart materials for the control of sophisticated systems, especially in the rotorcraft research field, calls for availability of adequate analysis tools.

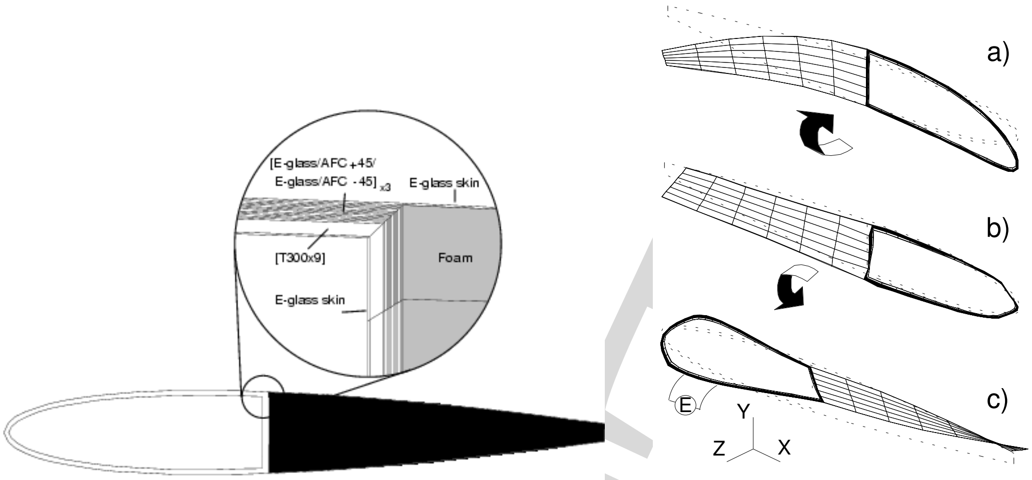

Figure 8: ATR blade section; left: ply sequence; right: warping: a) bending, b) twist, c) voltage.

While a relatively simple implementation of active devices such as piezoelectric actuators can be emulated by resorting to simplified methods, like the pin-force, a more detailed analysis is required when the smart materials are deeply embedded into the host structure and their total coupling becomes significant. To this purpose, the beam section analysis formulation presented in [4, 5] has been extended to the analysis of beam sections with arbitrarily shaped and oriented piezoelectric inclusions [8]; at the same time, the finite volume beam has been extended to allow to consider the fully coupled effect of the piezoelectrics to the internal straining of the beam element. The most significant application is represented by the analysis of the *Active Twist Rotor* currently investigated by Army/NASA/MIT. It consists in embedding the piezoelectric *Active Fiber Composites* into the rotor blade to obtain electrically controlled twist induction and thus to exploit the aerodynamic coupling with the twist to introduce loads into the rotor blade [9]. Figure 8 shows the active twist blade section warping due to unit bending, twist and electric loads.

8. HYDRAULICS

The last extension of the formulation in a multidisciplinary sense is represented by the integrated modeling of hydraulic system components. The objective is the capability of simultaneously modeling a comprehensive system. A recent application consisted in reproducing the active control analyses of the tiltrotor model with a detailed modeling of the hydraulic system, which basically confirmed the initial results, in which the dynamics of the control system were accounted for by simply filtering the inputs [10]. A complete review of this work is under progress, in which the multibody approach will be used as a means to synthetize an “aeroelastic impedance” of the rotor that will be used to design the servo-hydraulic control system of a helicopter. Then the complete multibody model, with detailed nonlinear hydraulic control components, will be used to verify the dinamics and the stability of the integrated aeroservoelastic system. Figure 9 shows the pressures in one swashplate actuator and the internal couples at the wing root during a cyclic and a collective pitch maneuver.

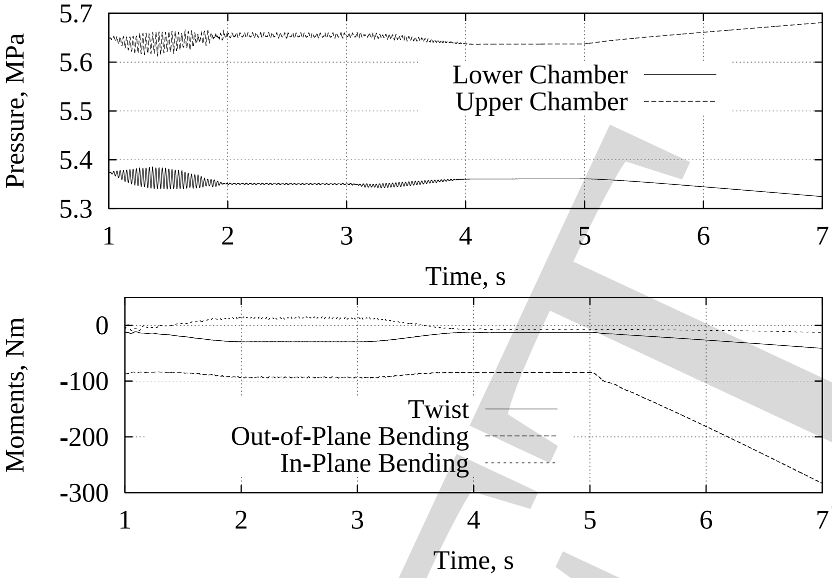

Figure 9: Pressure in one actuator and wing internal couples during a cyclic followed by a collective pitch maneuver

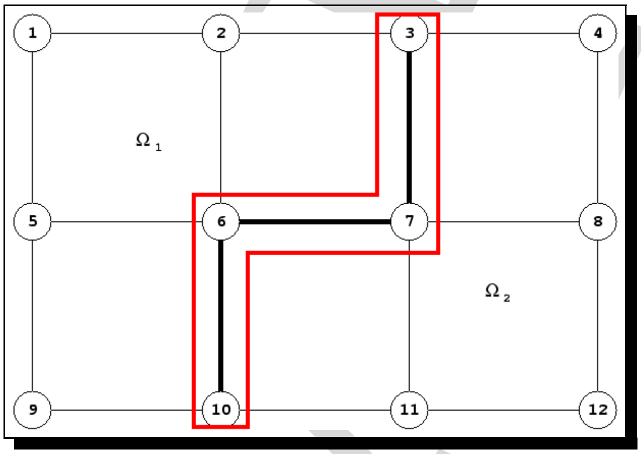

Figure 10: Element-based partitioning of the domain.

9. PARALLEL IMPLEMENTATION

The multibody analysis code has been recently implemented in a parallel framework, by using the message passing paradigm thanks to the MPI standard library. The problem is partitioned in a set of computationally balanced subdomains by an automatic partitioning algorithm that minimizes the interface size and thus the communication overhead. The partitioning is element-driven, i.e. elements belong to one subdomain only, while the "nodes", in the broader sense of degrees of freedom shared by different elements, may fall on the interfaces between partitions. Figure 10 sketches the partitioning. Each subdomain is assembled and solved locally by the *Schur Complement Technique*, also known as "substructuring" to structural engineers, which allows everything but the interface problem to be solved concurrently. Since rotorcraft models, with collocated aerodynamics such that implemented by the strip theory, represent a clear example of a(n open) tree, with possibly a very neat and limited interface if the partition is made at some blade station, the

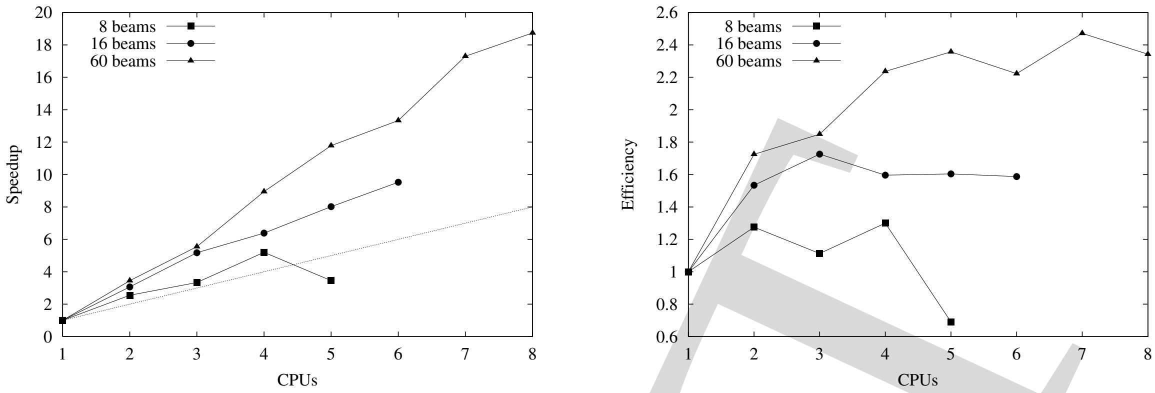

Figure 11: Speedup and efficiency of parallel computations on a HP 4000 with 8 CPU

algorithm proved very effective, with impressive speedup and efficiency figures, as shown in Figure 11. It refers to the analysis of the WRATS system, where the number of beam elements that are used to model the rotor blades is increased to an unreasonable level of 60 (which means 120 nodes) per blade to assess the scaling properties of the algorithm. It has been tested on both *Shared Memory Processors* (SMP), a 8 CPU HP-UX 4000, and on a cluster of PCs (500 MHz Dual-Pentium III), with comparable scalability results.

CONCLUSIONS

The multibody global modeling paradigm is becoming a mature analysis tool for industrial rotorcraft applications. Its penetration in the rotorcraft industry has been delayed by the availability of well proven, dedicated comprehensive analysis codes. However, the growth of interest for systems with a higher degree of sophistication, such as hingeless and bearingless rotors, nonlinear elastomeric bearings, and the introduction of new configurations, such as tiltrotors, that require the analysis of complex maneuvers in excess of conventional trim and stability investigations showed the limitations of dedicated codes and is giving the multibody approach a chance to prove its suitability to this purpose. This paper gave an overview of the efforts that have been made at the Department of Aerospace Engineering of the University “Politecnico di Milano” towards the multidisciplinary analysis of rotorcraft systems. Our Department is strongly committed in exploring multibody rotorcraft analysis; the code that has been developed to this purpose, MBDyn, will be made available to the Open Source community in the near future.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the role of Dr. G. Bindolino in the early investigations on the free-wake integration with the multibody analysis, the contribution of Mr. F. Felippone in implementing the modal flexibility module and that of Mr. L. Puggelli in the hydraulics module; finally, the role of Mr. G. Quaranta in developing the parallel implementation. Mr. S. Marazzani and Dr. G. Gilardi deserve a mention for their role in developing the finite volume beam element and the fixed step integration algorithm.

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