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Full three-dimensional investigation of structural contact interactions in turbomachines

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ABSTRACT

Minimizing the operating clearance between rotating bladed-disks and stationary surrounding casings is a primary concern in the design of modern turbomachines since it may advantageously affect their energy efficiency. This technical choice possibly leads to interactions between elastic structural components through direct unilateral contact and dry friction, events which are now accepted as normal operating conditions. Subsequent nonlinear dynamical behaviors of such systems are commonly investigated with simplified academic models mainly due to theoretical difficulties and numerical challenges involved in non-smooth large-scale realistic models. In this context, the present paper introduces an adaptation of a full three-dimensional contact strategy for the prediction of potentially damaging motions that would imply highly demanding computational efforts for the targeted aerospace application in an industrial context. It combines a smoothing procedure including bicubic B-spline patches together with a Lagrange multiplier based contact strategy within an explicit time-marching integration procedure preferred for its versatility.

The proposed algorithm is first compared on a benchmark configuration against the more elaborated bi-potential formulation and the commercial software Ansys. The consistency of the provided results and the low energy fluctuations of the introduced approach underlines its reliable numerical properties. A case study featuring blade-tip/casing contact on industrial finite element models is then proposed: it incorporates component mode synthesis and the developed three-dimensional contact algorithm for investigating structural interactions occurring within a turbomachine compressor stage. Both time results and frequency-domain analysis emphasize the practical use of such a numerical tool: detection of severe operating conditions and critical rotational velocities, time-dependent maps of stresses acting within the structures, parameter studies and blade design tests.

1. Introduction

With the endlessly growing contribution of full three-dimensional nonlinear analyses in structural components design, aircraft engine manufacturers strongly depend on the development and use of modern numerical tools. Related computational

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strategies traditionally based on the standard Finite Element Method routinely address structural configurations involving nonlinear kinematic descriptions, finite strains, constitutive laws with plasticity, crack propagation, nonlinear temperature gradients or unilateral contact constraints together with friction conditions, all within commercial software packages. Nevertheless, investigations requiring the enforcement of non-penetration constraints are still prone to numerical robustness issues that often necessitate in-house tools dedicated to very limited classes of problems.

In this context, the present study focuses on the development, validation and use of a three-dimensional contact algorithm devoted to the examination of blade-tips/casing structural contact interactions in modern turbomachines. These structural contacts are consequences of the implementation of improved energy efficient technologies affecting the operating clearances between the rotor and the surrounding stationary casing components potentially yielding severe damages [1–3]. Exploration of these phenomena demands meticulous attention on the considered solution method and related assumptions. Among the commonly used approaches in nonlinear dynamics (harmonic balance and shooting methods, analytical derivations and perturbation techniques, nonlinear modal analysis to name a few), time integration is given preference in the present work for its versatility and due to the complexity of the investigated phenomenon. As shown in previous studies involving two-dimensional models [4], the forward increment Lagrange multiplier approach within an explicit time-marching technique [5] stands as a reliable strategy for this class of problems and is here extended to full three-dimensional configurations [6]. Special consideration is given to large sliding and high tangential relative velocities between blade-tips and surrounding casings.

The novelty of the suggested approach lies in the efficient combination of several ingredients which have been already proposed for other matters:

(1) Construction of reduced-order models of large scale systems embedding centrifugal stiffening, *i.e.* dependence to a rotational velocity [7],
(2) Explicit time-stepping technique dedicated to unilateral contact and dry friction conditions,
(3) Contact interface smoothing procedure.

For a given blade design, the introduced numerical tool is able to provide a full cartography of its nonlinear frequency response (displacements, strains, stresses, contact forces) over a user-defined range of rotational velocities, in no more than few hours on a standard computer. By contrast, in commercial codes, centrifugal stiffening first necessitates a static pre-calculation for each investigated rotational velocity. This static computation requires a full, often very large (up to 1.5 million degrees of freedom), finite element model. The construction of reduced-order models directly embedding centrifugal stiffening significantly improves the numerical efficiency of the proposed strategy with respect to commercial softwares. The introduced tool is also versatile in such a way that existing meshing procedures implemented in industrial frameworks do not have to be modified. In this regard, consideration has been given to B-spline [8–11] surface patches.

Contact problems are inherently nonlinear since the contact area is *a priori* unknown and the respective hybrid contact pressure/displacement boundary conditions are part of the sought solution. The main difficulty lies in the constitutive laws of contact and friction expressed by non-smooth multivalued force–displacement relationships. From a mechanical engineering viewpoint, three groups of methods are usually preferred for the numerical treatment of such laws since they directly provide a physical sense to the quantities of interest: (1) the penalty method [12,13], (2) the Lagrange multiplier method [14,15] and (3) the augmented Lagrangian method [16]. While the penalty method depends on a parameter that allows a loosely controlled violation of the constraints between the structures, the Lagrange multipliers, which represent the contact reaction forces when convergence is reached, exactly enforce the non penetration conditions.

In a FEM context, unilateral contact and friction conditions are especially challenging due to the constant switches in the state of the constraints stemming from the spatial discretization. The contact zone is represented by a surface which is only piecewise differentiable, and most commonly of low order of continuity. As a consequence, numerical jumps in contact forces are typically encountered. These non-physical jumps can cause serious errors in the resulting simulated stresses and forces and smoothing methods are often required. A higher order of continuity can be prescribed by directly using $\mathcal{C}^n$ compatible and geometrically curved elements. Unfortunately, these elements are known to feature numerical difficulties [17] that may be overcome in an original fashion. Among possible strategies that have revealed themselves useful over the past few years [18], Bézier curves, Hermite and Bernstein patches [19], Overhauser segments [20], the diffuse approximation approach [21], the B-splines [8–11] and the non-uniform rational B-splines (NURBS) [22,23] stimulated a number of interesting investigations. While preserving the original meshes, they remove the facetization issues, ease the contact transition and then increase the convergence rates of the dedicated contact algorithms. Industrial environments may greatly benefit from such implementations since they simplify meshing procedures by allowing the use of a broader class a finite elements. All these mathematical objects are characterized by their own specific advantages and drawbacks (control points interpolation, refinement, knots insertion, internal subdivision) and the Bézier and B-spline curves are the most popular forms to date. In the present study, the cubic B-spline approach is adopted since it can easily be adapted to finite element meshes where the current positions of the nodes only are required.

For reliability and validation purposes, the proposed approach is first compared against the bi-potential method [24] and the Ansys commercial package. The formulation combining augmented Lagrange multipliers with the bi-potential method is capable of treating frictional contact constraints in a reduced system by means of a predictor–corrector solution algorithm. In addition, the bi-potential method leads to a single displacement variational principle and a unique inequality