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Assessment of 3D modeling for rotor–stator contact simulations

Mikhael Tannous [a,*], Patrice Cartraud [a], Mohamed Torkhani [c], David Dureisseix [b]

[a] *GéM, Ecole Centrale de Nantes, France*
[b] *Université de Lyon, LaMCoS, INSA de Lyon, CNRS UMR 5259, France*
[c] *LaMSID UMR EDF-CNRS-CEA 2832, EDF R&D, F-92141, Clamart Cedex, France*

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ABSTRACT

Most often the dynamic analysis of rotor-to-stator rub is performed using 1D models. This leads to a small computational cost, but the reliability of the results is difficult to assess. This research work compares and analyzes the results of 1D and 3D rotor–stator contact problems, for different contact conditions more and less severe. The rotor vibrations are due to rotating imbalance at a given constant rotating speed. In this paper, it is shown that regarding the rotor orbits, the 3D and 1D models responses are very close. However, using a 3D model improves the simulation results. The 1D model actually suffers from limitations resulting from rigid-body displacement assumption of the rotor's cross-section, which originates approximations in the rotor-to-stator contact modeling. Thus, the friction torque generated by the contact is overestimated in a 1D model. The 3D model, however, can present some local effects in the vicinity of the contact zone.

1. Introduction

An accidental blade loss causes a rotor unbalance which leads to rotor-to-stator contact while the turbine is slowing down and crosses a critical speed.

Rotor–stator contact can lead to diversified consequences (cf. [1]). It may be permanent like a full annular rub with a forward synchronous whirl, or with a backward whirl. This later can be a rolling without sliding called a dry whirl (or a dry friction backward whirl) and can also be a rolling (with friction) with a sliding in the opposite direction of the spinning (dry whip). The intensity of the friction forces is the main factor behind the dry whip phenomenon [2]. Therefore, the friction coefficient [3], an the rigidity of the rotor and of the stator are the main factors [4] involved.

The rotor–stator contact can be intermittent, i.e., with rebounds. Rebounds can be periodic, quasi-periodic or chaotic [5].

The eigen modes of the rotor–stator system may change due to the coupling that occurs during the interaction phase [1,6]. Local zone plastifications may also lead to eigen mode changes.

Thermo-mechanical effects are also observed. In fact, the rotor–stator contact energy is transformed to heat that causes local expansions leading to supplementary unbalance and reduces the rotor–stator gap distance [7]. Generally, most of this heat is received by the rotor causing it to deflect (the Newkirk phenomenon) [8]. Thermo-mechanical effects can lead to

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[*] Corresponding author. Tel.: +33 240 371 503; fax: +33 240 372 573.
E-mail address: mikhael.tannous@ec-nantes.fr (M. Tannous).

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spiral vibrations. This has been highlighted on a Jeffcott rotor in Sawicki et al. [9] and on real machines in Bachschmid et al. [10].

However, if the rotor is performing a free rotation after a blade loss, slowing down can occur. Roques et al. [11] remains one of the few research studies in the literature to deal with the slowing down of a turbine then leading to rotor to stator contact when passing through a critical speed. The authors highlight the effect of the friction coefficient, and of the stator rigidity on a turbine slowing down behavior. An analytical model was used in Braut et al. [12] to study the Jeffcott rotor slowing down due to its contact with a suspended rigid stator.

It is obvious that the rotor–stator contact problem is a complex and highly nonlinear problem, presenting both multi-physical (vibrations, contact, thermo-mechanical effects, etc.) and multi-scale (local deformations, etc.) phenomena that are complicated to model and to take into account correctly. In the literature, assumptions are made and it is difficult to assess their validity, even if comparisons with experimental results are provided. As mentioned previously, rotor slowing down and Dry Whip depend highly on the friction torque and the rigidity of the system. However, the first models in the literature to deal with rotor–stator contact problems are based on a simple Jeffcott rotor [13]. Moreover, the rotational velocity is constant, and is kept so along the rotor–stator contact phase by a compensating torque. These simplified models are described by differential equations and solved analytically, neglecting the gyroscopic effects [14].

One of the main drawbacks of these simplified models is the rigid body assumption for the rotor and stator modeling. A way to improve the model accuracy while limiting the computational coast consists in using 1D models based on beam finite elements. This has been proposed recently in Peletan et al. [15] for the analysis of an industrial EDF turbine with a harmonic balance method (see also [16]). The rotor to stator contact has also been studied in Roques et al. [11] with the same type of beam model. The transient response is calculated with a time integration scheme. Though industrial examples have been considered in these two previous papers, the approximations resulting from beam assumption and thus the beam to beam contact for the rotor to stator contact modeling are difficult to assess. The aim of this research study is to assess the need for more realistic models, i.e., 3D models for rotor–stator contact problems. This is an up-to-date issue if we examine the literature on the blade/casing contact problems. In fact, blade/casing contact problems involve physical aspects and require modeling techniques that present important similarities with rotor–stator contact problems [17]. Most of the research developments in the literature use beam models to simulate blade/casing contact interactions. However, the need for 3D models for a better understanding of blade/casing contact has recently appeared [18]. Indeed, local plastifications, surface coating extraction, local thermo-plastic effects, etc. cannot be seen unless a 3D model is used. The contribution of 3D modeling to blade/casing problem simulations raises the question of the validity of simplified beam models for rotor–stator contact problems. In fact, rotor–stator contact problems involve more complex modeling and physical aspects than those of a blade/casing contact problem. For instance, a mistaken friction torque estimation can lead to a dry whip behavior, in spite of a forward synchronous whirl. Such misleading conclusions can occur on simplified rotor–stator contact models since such models are not capable of a rigorous presentation of the contact surfaces and the physical aspects of surface to surface contact and friction.

This paper aims at illustrating the contribution of a 3D finite elements modeling of the rotor–stator contact interactions and consequently the limits of a simplified 1D model, by comparing the results of both models. Numerical examples are constructed to be consistent with industrial EDF turbines. However some data have been changed for confidentiality purposes.

1D and 3D simulations are carried out with the open source finite element software *Code_Aster* [19].

The paper is organized as follows. Firstly, the contact algorithms and the time integration techniques adapted to the problem are exposed. Then, the rotor–stator system is presented, and three application examples highlight the main contributions of a 3D model to rotor–stator contact problems.

2. The contact problem and the solution techniques

The contact/friction problem is a highly nonlinear complex problem. Solving a contact problem requires first to solve a geometric problem relative to the position of the two contacting bodies, and then to solve the incremental contact problem that enables one to obtain the contact pressure from which depends the friction force [20]. The computational cost and the stability of the solution depend also on the choice of the time integration technique.

2.1. The geometric and optimization problem

The master–slave formation [21] remains one of the most popular methods for solving the geometric problem. Solids S_1 and S_2 in Fig. 1 are susceptible of contact. The geometric problem consists in calculating the distance between the master and the slave surfaces, respectively Γ_1 and Γ_2. The nodes of Γ_2 are projected on Γ_1 and the distance between the two surfaces is computed as

$$g_n = \min_{x_1 \in \Gamma_1} \| x_1 - \overline{x}_2 \| \tag{1}$$