1. Introduction

Periodic unsteadiness is inherent to flows in gas turbine engines, and in consequence very many studies have been devoted to the understanding of unsteady flows in turbomachines over a large number of years. There are seminal investigations that have delved into the theoretical (e.g. Tyler and Sofrin [1] and Rangwalla and Rai [2]), experimental (e.g. Dring et al. [3], Dunn and Haldeman [4]), and computational (e.g. Rai [5], Giles [6]) aspects of rotor-stator interactions. In addition, reviews of the state of the art are available (Greitzer et al. [7] and Sharma et al. [8]) as well as more general introductions to the subject (e.g. Paniagua and Denos [9]). In recent reviews of turbine durability and aerodynamic predictive tools, respectively, Dunn [10] and Adamczyk [11] have made the point that the fidelity of flowfield predictions has increased accordingly as the state-of-the-art for CFD calculations in the gas turbine industry has progressed. The increased predictive capability of turbine design codes has allowed for better turbomachinery designs and improved understanding of the physical mechanisms that are prevalent in turbomachines, especially when used to compliment experimental findings.

Greitzer et al. [7] discussed time-varying flowfields and the aero-mechanical excitation that can result from such unsteadiness. The authors stated that, in general, levels of unsteady forcing that give rise to High-Cycle Fatigue (HCF) problems during engine development had to that time not been well predicted. They described the current design process for turbine blades as one of resonant-avoidance. Modern structural-analysis tools are used to predict the natural frequencies of vibratory modes with acceptable accuracy, and these are plotted versus wheel speed on a Campbell diagram along with the frequencies of expected stress drivers in the system. Fig. 1.1 is one such diagram for the stainless-steel high turbine blade tested in the code validation study described in Section 3, below. A typical design practice might encompass ensuring that there are no expected resonances for any of the lower-order modes in the operating range of the machine (a turbine rig in the case of Fig. 1.1). However, sometimes this design practice is not feasible. So, Greitzer et al. [7] concluded that blade forced-response and the high-cycle fatigue failures that can result from it were of sufficient interest to the gas-turbine community that "…a decrease in the level of empiricism [in that area] would be of significant value in the engine development process." Practically, this meant that faster and more accurate predictions of the magnitudes of unsteady forcing functions were required.

Toward that end, developments in predictive methods such as multi-grid techniques and implicit dual time-stepping, coupled with parallelization of codes (Ni [12]) have made it possible for designers to execute 3-D, unsteady Navier-Stokes analyses routinely during the design cycle. So, designers can now routinely predict periodic-unsteady forcing functions and the calculation of resonant stresses in multi-row turbomachinery is now widespread in the industry [13-19]. Consequently, it is now possible to make design changes as necessary based on the outcome of such calcutions. Also, short-duration experimental facilities that allow for accurate modeling of modern gas-turbine flowfields (e.g. Jones et al. [20] and Dunn et al. [21]) are often used to assess the capabilities of state-of-the-art codes. In particular, the abilities of the codes to predict both the time-averaged and time-resolved pressure loadings on transonic airfoils were investigated (e.g. Rao et al. [22], Busby et al. [23], Hilditch et al. [24], and many others [25-28]). This has even been extended to include an assessment of the structural response due to forcing by Kielb et al. [29] and Hennings and Elliot [30] as well as both the aerodynamic and mechanical damping Kielb and Abhari [31]. In addition, design-optimization systems have been used effectively in conjunction with steady-state flow solvers to reduce the strength of shock waves emanating from transonic turbine blades and decrease interaction losses as well as, presumably, resonant stresses by Jennions and Adamczyk [32].

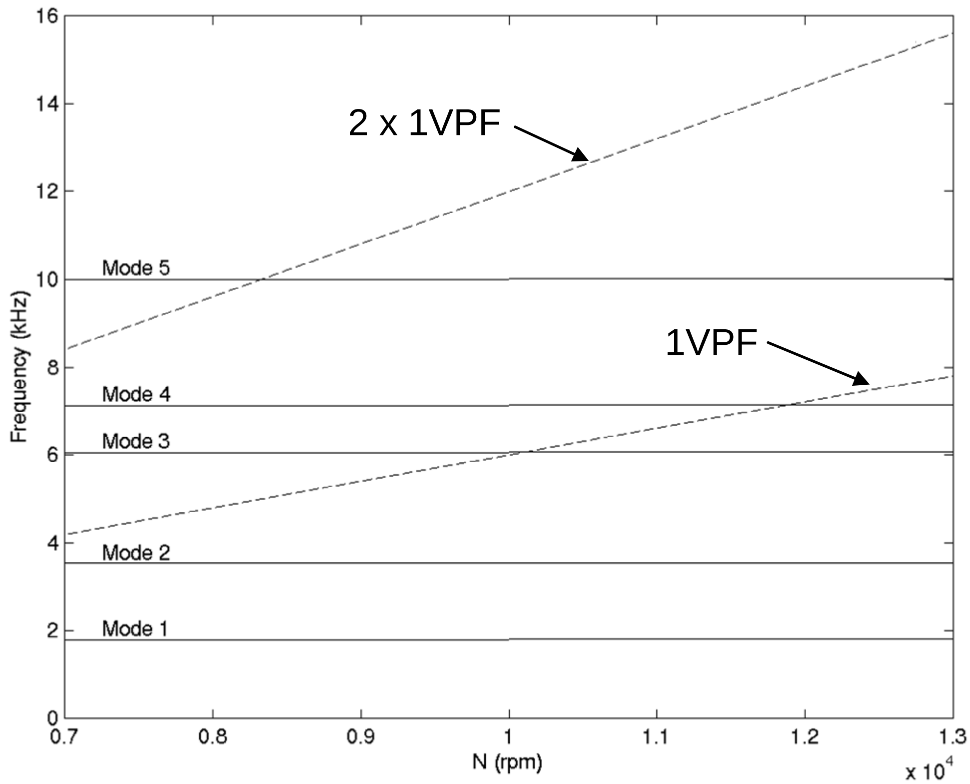

Fig. 1.1 Campbell diagram for a turbine blade tested in a short-duration rig

Turbomachinery designers often employ both steady-state and time-resolved predictive tools during the development of new engines. The major difference between the methods is the numerical treatment of the inter-row boundary. For steady-state turbomachinery simulations, common methodologies include the average-passage formulation of Adamczyk [11] and the mixing plane as employed in the Ni code [12, 33-35]. In the latter, the flow from an upstream blade row is circumferentially averaged and then the flow properties are passed into the downstream row as a radial profile. For many situations the difference between the steady-state flowfield and the time-average of an unsteady solution is minor. However, it is the time-resolved information that is often of most critical importance to the designer, as in the case of predicting resonant stresses in the machine.