Abstract

Sustainable electricity production has always been a very complex engineering challenge, as the amount of energy required daily by human activities is extremely high. Nowadays, most electricity is produced using steam and gas turbines, or combined cycle turbines. New-generation turbines can achieve very high efficiency, but the problem of CO_2 emissions remains a difficult challenge to overcome, as their operation is still linked to the use of fossil fuels. The energy market is evolving very quickly, and there is a growing trend towards electricity production from renewable sources. In particular, the possibility of producing electricity through nuclear fusion is becoming a reality. In fact, many companies, including Ansaldo Energia, have joined the ITER (International Thermal Experimental Reactor) program, which involves the construction of a working demonstration nuclear fusion reactor. The steam turbine that will be powered by this reactor is designed and manufactured by Ansaldo Energia. The last stage turbine blades are subjected to high stresses during turbine operation, which are caused by forced vibrations induced by the fluid-blade interaction. The vibration amplitudes may reach critical values, causing HCF (High Cycle fatigue) problems and the blades catastrophic failure. To avoid structural failure, dry friction devices are used to mitigate vibrations, dissipating a portion of the kinetic energy of the system. The dry friction devices commonly used for turbomachinery applications are shrouds, snubbers and underplatform dampers. These devices base their operation on the relative motion, caused by vibration, involving the contact surfaces between two adjacent blades. The relative motion between two surfaces in contact generates frictional forces, which cause the dynamic response of the system to be non-linear, as they depend on the relative displacements. This leads to the necessity to adopt a non-linear tool to predict the blades forced response considering the frictional forces effect.

The AERMEC research group at the Polytechnic University of Turin has developed a tool for Ansaldo Energia for the non-linear forced response computation of turbine

blades with friction contacts. For convenience of notation, this tool will simply be referred to as the Ansaldo's non-linear tool in this doctoral thesis.
the Ansaldo's non-linear tool is capable to compute the non-linear displacements field of the reduced blade model, taking as input the reduced stiffness and mass matrices, but is not able to compute the non-linear dynamic stresses because the reduced model does not include the FEM model elements. This represent a critical drawback in the mechanical design cycle because to predict the blade fatigue life is mandatory to compute the dynamic stresses amplitude.
Ansaldo Energia is one of the partners in the ITER (International Thermal Experimental Reactor) program, a European project that aims to build a demonstration power plant (DEMO), capable of powering the Ansaldo steam turbine and thus producing electricity without CO_2 emissions. The structural integrity of the nuclear reactor is guaranteed by the toroid, that has the crucial function on confining the high temperature plasma with a powerful magnetic field. The toroid has to handle very high currents for generating the magnetic field, this leads to its overheating.
At the current state of the art,to avoid this, the nuclear fusion reactor must be shut down and restarted periodically, causing the turbine to operate in transient conditions where the steam flow rate is extremely low. Very low steam flow rates can power the first stages, but the last stage is dragged by the previous ones and operates in compressor mode, dragging the residual steam in the chamber. These particular conditions are known as ventilation conditions, which cause asynchronous excitation, rotating stall cells and an increase in blade temperature. Under these conditions, the blades of the last stage can vibrate with very high amplitudes, which is why it is important to use mechanical devices to reduce these amplitudes and to have a robust procedure in place to predict the stresses on the blade, taking into account the effect of friction contacts.
This doctoral thesis deals with the development of a robust procedure for computing the dynamic stresses in turbine blades taking into account the friction contacts behavior during forced vibrations. This procedure will be applied on the last stage blades of the steam turbine designed by Ansaldo Energia, that will be powered by the nuclear fusion plant. The procedure developed during this doctoral program has the ultimate goal of calculating dynamic stresses, but to achieve this, it was necessary to perform some intermediate steps. The first problem addressed during this PhD concerns the generation of reduced mass and stiffness matrices. It is important to generate a reduced model that takes into account both the effect of centrifugal force

and the effect of static contact forces but does not include ANSYS contact elements. This was achieved by performing a preliminary static analysis with contact elements on the contacting surfaces, extracting the contact forces into a local reference system that is consistent with the blade deformation, and finally performing a second static analysis without the contact elements but importing the contact forces calculated in the preliminary analysis as external forces. The second problem encountered was the generation of a preload matrix on the contact nodes that takes into account the large deformation of the blade, thus avoiding the Ansaldo's non-linear tool convergence problems. The solution to this problem is found in the previous step, where the static contact forces, which constitute the pre-loads, are extracted into a local reference system that is defined on the deformed geometry.
The last problem addressed in this doctoral thesis is the calculation of stresses on the blade, taking into account the behavior of friction contacts during vibrations. As mentioned above, it is not possible to calculate the stress state in the Ansaldo's non-linear tool, so to overcome this problem, the friction forces calculated with the Ansaldo's non-linear tool in the frequency range defined for the non-linear calculation were extracted, and a linear harmonic analysis was then performed in ANSYS on the full FEM model, importing the friction forces as external harmonic excitations. This step allows the stress state on the blade to be calculated taking into account the friction forces. A check that was performed before the stress calculation was a comparison between the non-linear frequency response curve calculated with the Ansaldo's non-linear tool and that calculated with ANSYS, in order to ensure a correspondence of the non-linear displacements and, consequently, a correct evaluation of the stress state.
The nuclear fusion reactor is currently under construction, so the aerodynamic excitations under ventilation conditions are not known, but the procedure described so far constitute a robust a mechanical design tool for turbine blades that can be used in the future to evaluate the dynamic stresses on the blade with realistic aerodynamic excitation values.