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Nonlinear Model Predictive Control strategy for steam turbine rotor stress

S. Dettori[a]*, A. Maddaloni[a], V. Colla[a], O. Toscanelli[a], F. Bucciarelli[b], A. Signorini[b], D. Checcacci[b]

[a] *Scuola Superiore Sant'Anna, Via Moruzzi 1, 56124, Pisa, Italy*

[b] *Baker Hughes a GE Company, Via F. Matteucci 2, 50127, Firenze, Italy*

Abstract

The paper proposes a Nonlinear Model Predictive Control strategy for the control of steam turbines rotor thermal stresses, which exploits the approximation of the turbine rotor as an infinite cylinder subjected to external convection. The Nonlinear Model Predictive Control allows optimizing the control strategy in the long term, by significantly reducing the machine start-up time during the power up ramp. This study proposes two different control strategies: the former one is based on the control of the Heat Transfer Coefficient, correlated to the inlet valve stroke. The latter one is based on the control of Heat Transfer Coefficient and the boiler steam temperature reference. Both strategies achieve good results in shortening the start-up time. The overall approach is validated and currently under development on Programmable Logic Controller platforms to the aim of code optimization.

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Keywords: Rotor Stress Control, Nonlinear Model Predictive Control, Power Startup

Nomenclature

FEA	Finite Element Analysis ST	NMPC	Nonlinear Model Predictive Control
CSPP	Concentrated Solar Power Plant	PID	Proportional Integrative Derivative
HTC	Heat Transfer Coefficient	PLC	Programmable Logic Controller
LP	low Pressure	RSC	Rotor Stress Controller
MPC	Model Predictive Control	ST	Steam Turbine

* Corresponding author. Tel.: +39 050 882330.
E-mail address: Stefano.dettori@santannapisa.it

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1. Introduction

Discontinuous operation of Steam Turbines has progressively become more frequent for industrial power generation due to the diversification of energy market. Consequently, an optimized scheduling of electricity production, according to the prices of natural gas and electricity that may vary on the hourly/daily basis and a discontinuous load consumption, has become necessary. This involves an ever-increasing annual number of start-up and a relative aging of the machine, with the consequence of an increased risk of crack nucleation and propagation on the shaft [1].

While it is vital to optimize the geometric characteristics of turbomachinery, in order to minimize thermal stress, as described by Nowak [2] and Checcacci [3], a very important contribution is given by the start-up procedures [4], which are typically designed and optimized thanks to the experience of designers and field engineers. The main objective is to balance economic revenues from longer turbine operation and intelligent management of maintenance and risks and costs related to failures. Thanks to modelling efforts several kind of solutions can be designed to achieve this goal, such as described in the work of Dettori [5], where a neural network-based technique has been exploited as a soft-sensor for variables difficult to reach, useful for the prediction of windage effects and aging of blades, or in the work of Spelling et al [6] where, in the context of Concentrated Solar Power Plants (CSPP), thermodynamic models and genetic algorithms are effectively exploited to study a combination of measures, useful to improve the power output.

Under variable steam conditions, as in the case of CSPP, the modelling is a fundamental requirement for increasing plant productivity, as allows to fine tune the control procedures or to study expert and intelligent control systems such as described by Dettori et al in their paper [7] where a simplified dynamic model of High Pressure and Low Pressure (LP) turbines and Fuzzy-PID techniques, allow to speed-up the power tracking transient during start-up and in general, in variable operative points.

The limit of rotor thermal stresses is a challenging problem, as they are difficult to be measured during ST normal operation without incurring in very relevant technical challenges. Furthermore, if inlet steam temperature is not a controllable variable, only the steam mass flow (valve stroke) can be used to limit the stresses. Historically the control of thermal stresses has been realized off-line by limiting the minimum start-up time of the turbine by specifying start-up curves as a function of casing temperature, the maximum rate of variation of inlet steam temperature, the maximum casing differential temperature. Many techniques have been exploited, from the more standard and computationally non-burdensome ones like PID control, such as described in the work of Casella et al [8], and Fuzzy Logic approach as in the paper presented by Boulos [9], to the more advanced ones such as Model Predictive Control (MPC), such as described by Nakai et al [10] through a linear model of stress and a linear programming routine, or in the work of D'Amato et al [11], where the start-up of a combined cycle power plant has been optimized by means of MPC. Banaszkiewicz proposes a control method based on a thermodynamic model of steam behaviour in turbine critical locations and relative thermal stresses, allowing to modulate the steam temperature reference as control action [12]. Another interesting approach has been proposed by Zhang et al [13] through a controller based on Pontryagin's Maximum Principle and an accurate model of heat transfer in the rotor, with the aim of controlling the steam inlet temperature to limit thermal stress. Sun et al. [14] propose a life extending control based on a damage model that estimates the cumulative damage and damage rate, and a polynomial controller which integrates the existing PID control. In general, in the state of the art emerges that the successful control strategy for limiting thermal stresses, seems to be the MPC.

In this context, within the project STECH, funded by the Region Tuscany, one of the research topic is related to the improvement of the start-up of steam turbines, and their more efficient operation. This paper presents the preliminary results of the application based on nonlinear MPC strategy to the improvement of steam turbines start-up after connecting to the grid, in the phase of power ramp control. In particular, in section 2 the modelling approach of rotor stresses based on heat equation has been described in detail, while in section 3 the nonlinear MPC strategy is formulated. Section 4 presents the two control scenarios, the former based on the control of Heat Transfer Coefficient (HTC), and the latter based on the control of both HTC and inlet steam temperature. Finally, section 5 provides some concluding remarks.

2. Rotor Stress Model

The mathematical formulation of the methodology to be used to evaluate thermal stress must have a limited computation time in order to be implemented into common current industrial control platforms. This implies that Finite Element Analysis (FEA), normally used for transient thermal stress evaluation, cannot be used and a simplified model needs to be derived. Experience from studies on the thermal transient thermos-elastic behavior of ST rotors have highlighted that most significant thermal stresses are due to differential expansion. A common approach (see for example Nakai et al [10]) to evaluate these stresses in a simplified manner, without losing information on material properties and global rotor is to use a cylindrical simplified model. A simplified cylinder model is described by the well-known heat equation in cylindrical coordinates:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) \tag{1}$$

With the following boundary conditions:

$$\begin{cases} \left.\dfrac{\partial T}{\partial r}\right|_{r=0} = 0 \\ -k\left.\dfrac{\partial T}{\partial r}\right|_{r=R_{ext}} = HTC(t)\cdot[T\,|_{R=R_{ext}} - T_{bulk}(t)] \end{cases} \tag{2}$$

where T is the rotor temperature as function of time t and radius r, HTC is the Heat Transfer Coefficient in [W/(m^{2}K)], T_{bulk} is the bulk temperature to be applied to the model (the steam temperature), ρ is the rotor density in [kg/m^3], C_p the rotor heat capacity in [J/kg K], k the rotor thermal conductivity in [W/(mK)].

The model is developed with some assumptions: it is one-dimensional, described as a cylinder axially infinite without considering axial temperature variations; it takes into account local change of material properties as a function of temperature ($k=k(T)$, $\rho=\rho(T)$, $c_p=c_p(T)$); the boundary conditions of the problem are the Neumann condition at the center and the Robin condition on the outer radius; the problem is time dependent since both HTC and T_{bulk} are a function of time.

In order to solve thermal transient problem online it has been chosen to use a finite differences forward Euler method with $\Delta r = r_{i+1} - r_i$ dividing the cylinder domain in n nodes:

$$T_j^{(i+1)} = f(T_j^{(i)}, T_{j-1}^{(i)}, T_{j+1}^{(i)}, \ldots) \tag{3}$$

where basically the temperature at the node j at the step (i+1) is a function only of temperatures at the previous step i. The convergence of the method obviously depends on the time step.

After the numerical discretization process, the model obtained for the distribution of rotor temperature can be reconducted to the following meaningful expression:

$$T^{(j+1)} = A^{(j)}\cdot T^{(j)} + B\cdot\varphi(T_N^{(j)}, HTC^{(j)}, T_{bulk}^{(j)}) \tag{4}$$

where $A \in R^{n\times n}$ is a tridiagonal matrix whose non-null terms have the following expressions:

$$a_{i,i}^{(j)} = 1 - \frac{\Delta t}{(\Delta r)^2}\alpha_{i-\frac{1}{2}}^{(j)}\left(1-\frac{\Delta r}{2r_i}\right) - \frac{\Delta t}{(\Delta r)^2}\alpha_{i+\frac{1}{2}}^{(j)}\left(1+\frac{\Delta r}{2r_i}\right) \tag{5}$$

$$a_{i-1,i}^{(j)} = \frac{\Delta t}{(\Delta r)^2}\alpha_{i-\frac{1}{2}}^{(j)}\left(1-\frac{\Delta r}{2r_i}\right) \tag{6}$$

$$a_{i+1,i}^{(j)} = \frac{\Delta t}{(\Delta r)^2}\alpha_{i+\frac{1}{2}}^{(j)}\left(1-\frac{\Delta r}{2r_i}\right) \tag{7}$$

In the previous expressions $\alpha^{(j)} = k^{(j)} \big/ \left(\rho^j \cdot c_p^{(j)}\right)$ is the thermal diffusivity evaluated locally Δr is the spatial discretization corresponding to the radius r_i and Δt is the time discretization. Particular attention has to be used for the term φ physically representing the heat flux transferred by convection to the cylinder

$$\varphi = a_{N+1}^{(j)} \cdot HTC^{(j)} \frac{2\Delta r}{k_{\left(T=T_N^{(j)}\right)}} \left(T_{bulk}^{(j)} - T_N^{(j)}\right) \tag{8}$$

where T_{bulk} is the steam bulk temperature. From a control theory standpoint, it can be observed how the cylinder model once discretized is similar to a Linear Time-Invariant system model. Differences arises when observing that the matrix A actually depends on the rotor temperature. In addition, for our case only the HTC can be directly controlled and the difference T_{bulk} - T_N influences the heat exchange between the steam and the ST rotor skin, and when the latter reaches the temperature of the rotor skin, the rotor temperature can not be controlled by *HTC* in any manner.

Once that the temperature has been properly discretized a similar procedure need to be applied for stress. The stress in cylinder can be expressed assuming a generalized plane strain formulation that basically leads to the following expression for the Von Mises equivalent stress σ_{eqv} evaluated at the external radius of the cylinder r = R.

$$\sigma_{eqv} = \left| \frac{\beta E}{1-\upsilon} \left(T\left(R\right) - \frac{2}{R^2} \int_0^R Trdr \right) \right| \tag{9}$$

where β is the thermal expansion coefficient and E is the young modulus. By using the trapezoidal rule, the integral can be approximated and through some rearrangements can be expressed in linear matrix form as follows:

$$\sigma_{eqv} = C \cdot T = \left[c_1 \quad c_2 \quad \dots \quad c_n\right]^T \cdot \left[T_1 \quad T_2 \quad \dots \quad T_n\right] \tag{10}$$

Once that this linear relationship has been highlighted the model is completed through a tuning activity based on the exhaustive examination of rotor detailed finite element models and through the creation of thermodynamic transfer functions correlating measurable thermodynamic quantities in the steam turbine with local values of heat transfer coefficient and bulk temperatures.

3. Nonlinear MPC formulation

Starting from the developed model, it is possible to define the nonlinear MPC problem. A possible approach is the maximization of the produced energy with a stress limited within a chosen limit range $\sigma_{max} \leq \sigma(i) \leq \sigma_{min}$. Several constraints complete the control problem, the minimum and maximum ranges of allowable power $P_{min} \leq P(i) \leq P_{max}$ and manipulated variables $u_{min} \leq u(i) \leq u_{max}$:

$$\min_u J\left(x,u\right) = \min_u \sum_{i=1}^{N_{pred}} \left(\mathbf{P_{max}} - \mathbf{P}\right)^T \mathbf{W_P} \left(\mathbf{P_{max}} - \mathbf{P}\right) + \Delta\mathbf{u}^T \mathbf{W_{\Delta u}} \Delta\mathbf{u} \tag{11}$$

In the objective function a cost term is included, which is related to the variation of the control, in order to smoothen the control sequence. $\mathbf{W_p}$ and $\mathbf{W_{\Delta u}}$ are, respectively, the weight related to the tracking of maximum power and the variation of the controllable variable.

The formulated problem is heavily nonlinear, as both stress-related constraints and the power are a non-linear function of the HTC, the steam temperature and the nonlinear dynamics of rotor temperature. The Nonlinear MPC (NMPC) problem is non-convex and this implies not only that it is difficult to find a global optimum, but also that in some operative points it may be difficult to find a solution within reasonable computation time. In this work several approaches have been exploited for the solution of this challenging control problem: the algorithm is based on the Sequential Quadratic Programming (SQP) as an efficient numerical optimization method [15]; the rotor stress and turbine models have been simulated with a sampling time that respect the convergence condition of the explicit numerical scheme in order to avoid the unstable behavior of the temperature dynamic; the prediction time horizon has been set in the range 30-60 minutes in function of turbine size and its thermal dynamic behavior, sufficient to forecast the future peak of rotor stress; the optimal control has been computed not every sampling time, but for a reduced number of time steps, uniformly distributed over the whole prediction time horizon, in order to reduce the problem dimensionality, and the intermediate values are obtained through a linear interpolation. In the control scenario where the only controlled variable is HTC, the steam temperature predictor is based on a linear extrapolation that has the same time horizon as the stress predictor. Furthermore, in order to decrease the computation time, the constraints have been verified for a reduced number of steps, thanks to the smooth dynamic behavior, and the number of algorithm iterations have been limited.

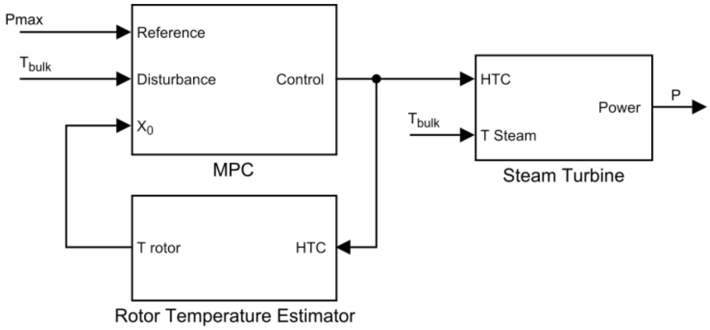

Fig. 1: NMPC control scheme of turbine HTC.

The controller, developed and tuned in Matlab/Simulink environment, is shown on Figure 1, which depicts two different blocks of the controller itself, the *MPC* that solves the optimum problem, and the *Rotor Temperature Estimator* that, starting from the current control, estimates the rotor temperature distribution (the state of the system), and the simulation of the turbine generated power.

4. Numerical results

As a benchmark of the NMPC approach for the RSC, two different scenarios have been designed and relative results have been analyzed and discussed. In the first, a LP steam turbine has been modeled and subjected to a cold power startup (rotor with an equal temperature distribution of 50°C) in conditions of uncontrolled steam temperature (the NMPC does not control the boiler steam temperature), with rapid variations, as in the case of CSPP. In the second, the same turbine has been subjected to a cold startup with the possibility of a limited controllability of the inlet steam temperature, in this case the second manipulated variable of the NMPC in addition to the turbine HTC. The duration of the mission in the simulations was set to 8000 seconds. Final results are shown in Table 1 e figure 2.

In particular, Figure 2 shows the achieved results in the first scenario, in the top left, the manipulated variable HTC; in the top right, the achieved stress during the startup and the its limit; in the bottom left, the produced electric power; in the bottom right, the inlet steam temperature and the temperature distribution in the turbine rotor.

Table 1 shows the main indexes that allow to validate the NMPC approach in the two different scenarios, the settling time $T_{startup}$ (time to reach the 95% of maximum power), the Energy Production in [MWh], the mean computation time *Mean(TC)*, and the standard deviation of the computation time *STD(TC).* Each index has been computed for the two different control scenarios.

In each scenario, the weights of the NMPC have been heuristically tuned, in order to guarantee the system stability, the robustness at varying of plant parameters and to satisfy allowable computational time, that in platforms such as PLC is the main constraint to guarantee the real time application of control algorithms.

Table 1: Test results of rotor stress control through NMPC approach.

Scenario	Tstartup [min]	Energy Production [MWh]	Mean(TC) [s]	STD(Tc) [s]
1 – Uncontrolled steam temperature	111	50.04	0.117	0.048
2 – Controlled inlet steam temperature	66.6	88.41	0.239	0.215

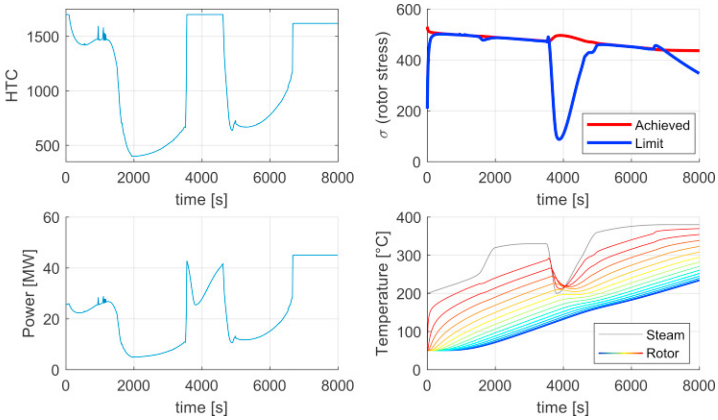

Fig. 2: Results of scenario 1, cold power startup with controlled HTC and uncontrolled inlet steam temperature.

5. Conclusions

This paper presents a nonlinear MPC approach to the control of rotor stress for the start-up of steam turbines during the phase of power ramp control. The control strategy implements within the algorithm an accurate modeling of heat transfer, based on the assumption of infinite cylinder. The model has been validated respect to the results of the steam turbine FEA models. The control approach has been tested for a low-pressure turbine in two different scenarios, in the former the control is based on the modulation of HTC, in the latter both HTC and the inlet steam temperature have been controlled. The results show the feasibility of the approach that allows to achieve fast startups with limited stress. Furthermore, the computation time are compatible with PLC platforms, for which the NMPC algorithm is in the phase of development.

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