Real-Time Model-Based Control System Design and Automation for Gelcast Drying Process

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Abstract Gelcasting is a new method for manufacturing advanced structural ceramics for use, for example, in the aerospace industry. The process involves a drying stage, where moisture, which constitutes approximately a quarter of the mass of the part, is removed in a commercial dryer. The control system design for the gelcast ceramic drying process is complicated by the requirement of minimizing the drying time while avoiding cracking during shrinkage of the part. This paper describes the application of the Lyapunov theory for finding an exponentially stablizing controller for the nonlinear drying model. A RealSimⓉRapid Prototyping model and the MATRIXxⓉdesign automation environment are used for real-time control, as well as feedback system implementation. It is shown that the proposed design and testing automation process with a user-friendly interactive animation (IA) graphical-user-interface (GUI) provides an effective and efficient environment for real-time control of the gelcast drying process.

Introduction

Gelcasting is a relatively new method for manufacturing advanced structural ceramics for use in the aerospace industry and elsewhere [3, 4]. The process involves preparation of a slurry of micron-

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sized ceramic particles (e.g., alumina or silicon nitride) in water with gel initiators, catalysts, and binders. Gelling is initiated after the slurry is cast in a mold. Moisture constitutes a quarter of the mass of the green part separated from the mold, which is removed by drying. The part is then gas-sintered for densification, and to burn out the polymer gel and binder. The final product is a near-net shaped part that requires very little machining.

Since the moisture in the gelcast part is removed during drying *via* the slow process of vapor diffusion through the porous solid, the drying stage is the longest stage in the gelcasting process, and can become a bottleneck in a manufacturing environment. Hence, it is necessary to design an optimal drying cycle whereby the drying period is minimized without causing any damage to the part. This paper describes a feedback system scheme for the gelcast drying process, as well as a real-time control automation environment. The final result is that the drying process is greatly speeded up.

A semi-empirical physical model for drying of gelcast parts was devised based on moisture diffusion through the part. Details of the model are given elsewhere [1]. Briefly, the drying process is divided into three stages. The first (linear) stage occurs when the moisture present relatively close to the part surface is removed at a constant rate. In the second (non-linear) stage, the drying rate decreases with time. The final (linear) stage of Knudsen-like diffusion is characterized by a small and constant drying rate. The part shrinks by 3-4% (linear dimension) during Stage 1. The actual switching point between stages depends on dryer conditions and part geometry. The model can either predict the drying rate when dryer humidity and temperature, and the gelcast geometry are specified, or predict the dryer humidity needed to attain a specified drying rate when dryer temperature and part geometry are specified.

The control system design for the gelcast ceramic drying process is complicated by the requirement of having the ceramic part dried in minimum time while avoiding cracking during shrinkage of the part in the very early stage of the drying process. While high drying rates (caused by low relative humidities and high temperatures) are desirable for faster drying, they increase the risk of cracking. The control system design consists of two parts. The first part is the determination of optimal recipes for gelcast drying processes to attain the shortest possible drying periods while avoid cracking. The second part is the design of a feedback system to enable the drying process track the recipes. This paper describes the application of the Lyapunov theory in finding an exponentially stabilizing tracking controller for the nonlinear drying model.

Real-time process experiments are conducted to validate any proposed recipes and feedback system design because no physical model for gelcast cracking is available for off-line numerical simulations. A RealSimⓉRapid Prototyping model and the MATRIXxⓉdesign automation environment[5] are used for real-time control, as well as feedback system implementation. As illustrated in this paper, the user-friendly GUI-based real-time control environment that has been implemented

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[5] RealSim and MATRIXx are trademarks of Integrated Systems Inc., Sunnyvale, California, U.S.A.

provides an effective and efficient environment for the real-time gelcast drying process control. This control automation scheme saves a significant amount of time in the design and control cycle for the drying process, and hence helps speed up the determination and validation of optimal recipes for various gelcast parts using data from several drying experiments. The controller has been tested on several rotors and stators manufactured for small gas turbines.

Feedback System Design for Gelcast Drying Process

A commercially available TenneyⓉdryer is used for gelcast drying. The dryer's temperature and humidity sensors are RTD and capacitative devices, respectively. An electronic MettlerⓉbalance is used as the mass sensor, while a MitutoyoⓉDigital Dial Indicator is used as the dimension sensor. Both have RS232 interfaces for sending data to the controller. The Dial Indicator is kept in stable contact with the gelcast surface. As the part shrinks, this contact sensor measures the dimensional change. The original nominal dimension is entered as tare so that the Dial Indicator reading is the new dimension.

The feedback control system design for the gelcast drying process has been cast as a tracking design problem: given an optimal set of temperature and mass-reduction rate recipes, design a feedback system so that the actual moisture mass-loss rate will follow the specified mass-reduction rate profile as closely as possible. The feedback signals used for this purpose are the temperature and humidity of the dryer, and the mass and dimension of the drying part. The reference inputs are the temperature and moisture mass-loss rate profiles (recipes).

The proposed feedback control system for the drying process of ceramic gelcasting is depicted in Figure 1, where the ”Dryer” model includes the existing commercial dryer with the PID controllers built in for the control of temperature and humidity in the dryer chamber, and the mass and dimension sensors. As is shown in Figure 1, the feedback control system consists of the following primary components:

1. Filters to reduce noise in the mass and the size (dimension) feedback signals.
2. Two versions of the physical model for gelcast drying used for feedback design:
   - The first version of the drying model referred as Drying Model 1 is used to evaluate the mass-reduction rate for the drying part with temperature and humidity as inputs to the model. The predicted mass of the drying part is then compared with the actual mass measured by the mass sensor, and the difference is used in the control algorithm to determine the desired mass-reduction rate. To predict the total mass of a drying part more accurately, the gelcast part is divided into multiple components. Both the stator and rotor are each divided into three components in the feedback control scheme (see

Figure 1) with Component 1 indicating the thickest one. The physical model is applied to each of the three components.

- The second version of the drying model is capable of predicting, with reasonable accuracy, the necessary dryer relative humidity to achieve the prescribed water mass-loss rate for the thickest component of drying part with the specified dryer temperature. This version is referred to as Drying Model 2 in Figure 1.

3. A control algorithm based on a Lyapunov function, which evaluates the controlled mass-reduction rate based on the mass feedback signal, the predicted total mass loss, and the mass-reduction rate profile. The controlled mass-reduction rate is then used as the input to the Drying Model 2 to determine the relative humidity necessary to attain the desired rate. Details of the control algorithm are given below.

4. A profile generator to calculate the temperature and the mass-reduction rate based on the recipes of the chamber temperature and the mass-reduction rate provided by the user. The dimensional signal is used to detect if the period of shrinkage, during which the gelcast part is most prone to cracking, is over. A more aggressive temperature and mass-reduction rate profile can then be adopted for drying which helps speed up the process.

The model-based controller is designed based on the Lyapunov theory [5]. Define a Lyapunov function V as

$$V(t) = \frac{1}{2}[m(t) - m_{\text{ref}}(t)]^2 \tag{1}$$

where $m(\cdot)$ is the feedback mass of the drying part and $m_{\text{ref}}(\cdot)$ is the reference mass. Differentiating $V(\cdot)$ yields

$$\frac{\partial V}{\partial t}(t) = [m(t) - m_{\text{ref}}(t)][\dot{m}(t) - \dot{m}_{\text{ref}}(t)] \tag{2}$$

Let

$$\dot{m}(t) - \dot{m}_{\text{ref}}(t) = -\beta[m(t) - m_{\text{ref}}(t)] \tag{3}$$

where $\beta \geq 0$ is the control gain to be chosen. Substituting (3) into (2), we have

$$\frac{\partial V}{\partial t}(t) = -\beta[m(t) - m_{\text{ref}}(t)]^2 < 0 \tag{4}$$

This scheme thus guarantees the feedback system will be exponentially stable, and have zero asymptotically tracking error.

Since the thickest component of the ceramic part determines the drying period, it is the one used in the Drying Model 2 to determine the relative humidity. Therefore the reference mass ($m_{\text{ref}}(\cdot)$) and the reference and the controlled mass-reduction rates ($\dot{m}_{\text{ref}}(\cdot)$ and $\dot{m}_c(\cdot)$) are defined with respect to the thickest component. On the other hand, the mass feedback signal ($m(\cdot)$) indicates the total mass of the part. Therefore, the control law in (3) is modified to:

$$\begin{aligned}\dot{m}_c(t) &= \dot{m}_{\mathrm{ref}}(t) - \beta\left[m_1(t) - m_{\mathrm{ref}}(t)\right] \\ &= \dot{m}_{\mathrm{ref}}(t) - \beta\left[\alpha(t)\cdot m(t) - m_{\mathrm{ref}}(t)\right] \qquad (5)\end{aligned}$$

where

$$\alpha(t) = \frac{m_1(0)+m_2(0)+m_3(0)}{m(0)}\cdot\frac{m_1(t)}{m_1(t)+m_2(t)+m_3(t)} \qquad (6)$$

Note that $m_1(\cdot)$, $m_2(\cdot)$ and $m_3(\cdot)$ respectively denote the predicted masses from the Drying Model 1 for the three components of the ceramic part. The first term on the right-hand side of (6), $\frac{m_1(0)+m_2(0)+m_3(0)}{m(0)}$, is the ratio of the sum of initial masses of the three components to the initial feedback mass of the drying part, which indicates the normalized factor between the masses of the modeled and the actual drying part. The second term on the right-hand side of (6) denotes the mass fraction of the thickest component.

Cracking is less likely in the post-shrinkage drying stages. Therefore the control law can play a more effective role through the choice of progressively larger values of the control gain, β, as shown below:

$$\beta = \begin{cases} 0 & \text{Shrinking Stage} \\ 0.05 & \text{Stage 1} \\ 0.1 & \text{Stage 2} \\ 0.2 & \text{Stage 3} \end{cases} \qquad (7)$$

Real-Time Process Automation for Gelcast Drying

For real-time process control, an efficient and effective design, implementation and testing automation environment is very desirable because it helps to reduce the period of design cycle significantly, e.g., from weeks to hours. To achieve this goal, it requires:

1. A hardware/software framework to communicate with the dryer for generating and sending control commands to the dryer, and for decoding sensor outputs from the dryer.

2. A reliable and efficient scheme to implement the controller in real-time, and interface with the dryer's sensors and actuators.

3. GUI (Graphical User Interface) IA (Interactive Animation) windows served as the operator interface which allows the user to initialize the serial communication with the dryer and display the output data of the dryer in real-time. It can also be used to decide the relevant data like the type of drying part, temperature and mass-reduction rate profiles, mass and size tares, etc.

4. An automatic data acquisition scheme which acquires selected input/output data at specified rates.

The RealSim Software of Rapid Prototyping Systems [2] developed by ISI provides an ideal and complete solution to establish an efficient and effective hardware-in-loop real-time control. The RealSim controller automates the development of real-time systems by combining graphical modeling software with real-time control hardware. A diagram describing the gelcast drying design/control environment is shown in Figure 2, where

- the RealSim AC-100/C30 model is a PC-based controller based on Texas Instruments (TI) 32-bit floating point digital signal processors (DSPs). The serial communication has been established between the dryer and the controller via a RS232 serial interface such that
    1. control commands containing desired temperature and humidity can be sent to the dryer from the controller;
    2. the readings of temperature and humidity in the dryer, and the mass and the dimension information are accessible to the controller.
- AutoCode is used to generate C executable code for the controller model. AutoCode is a very useful and reliable source code generator that bridges the gap between design and implementation by generating the downloadable code directly from the design database.
- the user can acquire selected input/output data of the controller at specified rates during real-time control via the RealSim facility. The raw data can then be converted into the ASCII format so that they can be used in Xmath for analysis.
- the main IA window as shown in Figure 3 is used for the following functions:
    1. Specifying the type of drying part. Although the choice is currently restricted to a rotor, or a stator or simply a test sample, it can be extended to include other ceramic parts as desired.
    2. Initializing the mass filter, and specifying the weight and dimension tares.
    3. Clicking on the Enable RS232 button to establish serial queries with the dryer model, and specifying the query period.
    4. Monitoring output states of the sensors.
    5. Reading the process time.
    6. Monitoring the trajectories of the mass of the part, temperature and humidity of the dryer, and the size of the part on a real-time basis.

7. Creating or modifying the TM (temperature/mass-rate) profile for the closed-loop control case. A TM IA window is shown in Figure 4 where the user can specify up to fifteen data sets of temperature, mass rate and corresponding linear transition period from the previous data.

   The control signals and data on the IA windows are used as inputs to the controller model. The feedback signals and the controller outputs are also directed to the IA windows where they are displayed in numbers, plots, toggles, etc.

An example of recipe profiles and real-time process control results for a specific ceramic rotor is given in Figure 5. The top two graphs indicate the temperature and the mass-reduction rate recipes, the middle graph shows the humidity in the dryer, and the last two show the filtered feedback mass and dimension of the drying rotor. It is seen from Figure 5 that the rotor can be dried out in about thirty five hours. The implementation of this controller has decreased the drying periods of the rotor and the stator by 65% and 90%, respectively.

Conclusion

This paper describes the application of the Lyapunov theory to the design of a model-based feedback controller for the nonlinear gelcast drying process. The controller uses a semi-empirical physics-based drying model correlating drying rate with dryer humidity and temperature, and part geometry. We have also described an automated design and real-time control environment built upon a RealSimⓉPrototyping model of MATRIXxⓉ, which is efficient and effective, and uses a user-friendly interactive graphical user interface. The implemented real-time feedback scheme has demonstrated consistent process results on rotors and stators of small gas turbines. It has helped reduce the period of design and control cycle of the gelcast drying process, which, in turn, has speeded up the determination and validation of optimal drying recipes. These optimal recipes, together with the feedback controller, have reduced the drying periods by 65% or more.

Acknowledgement

This work is partially funded by the Defense Advanced Research Projects Agency (DARPA, Cooperative Agreement Number N00014-95-2-0006) and administered by the Office of Naval Research (ONR). Funding balance and program execution is provided by the Advanced Structural Ceramics Virtual Company (ASCVC), led by AlliedSignal, Inc. The authors would like to express their gratitude to Dr. R. Kosut and Dr. S. Spain for their valuable suggestions about the controller design. The authors also benefited greatly from extensive discussions on the gelcast process with Dr. J. Pollinger, and Dr. O. O. Omatete and Dr. S. D. Nunn.

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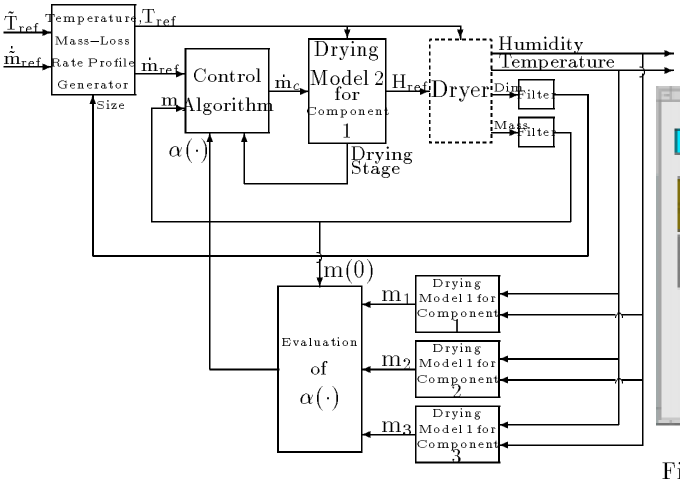

Figure 1: Feedback control system for gelcast drying process

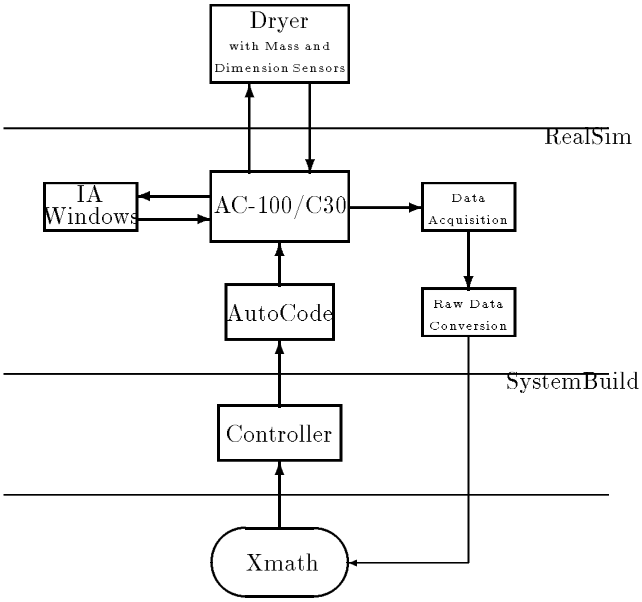

Figure 2: Basic structure of AC-100/C30 real-time control environment for gelcast drying process

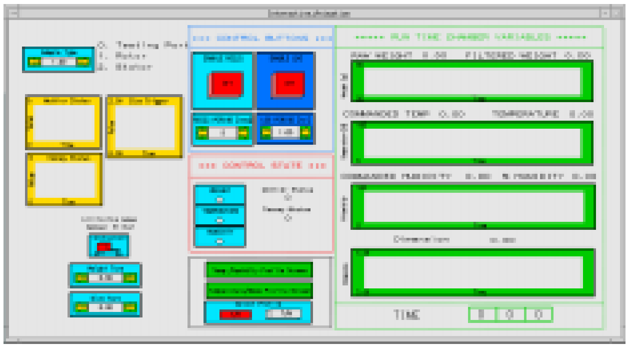

Figure 3: Main IA window for the gelcast drying process

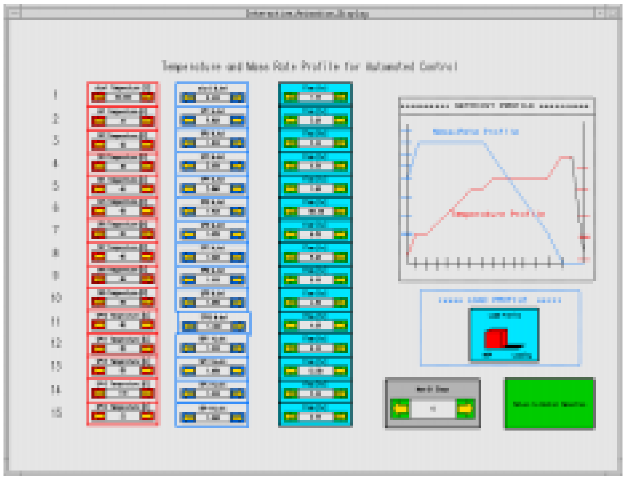

Figure 4: The IA window for editing the temperature/mass-rate profiles

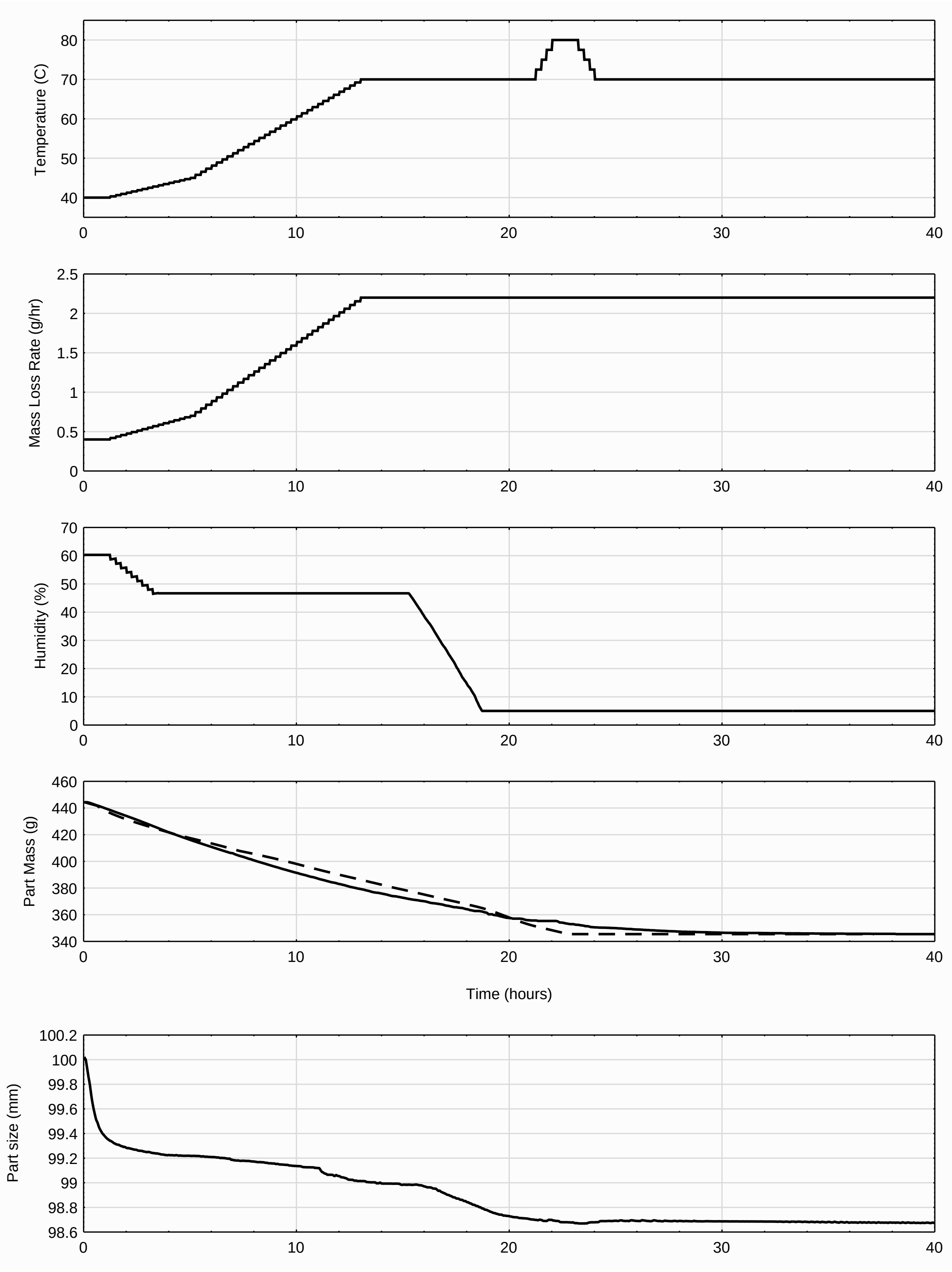

Figure 1: Real-Time process results for the turbine rotor: (from top) 1) commanded temperature profile, 2)commanded mass-reduction rate profile, 3) commanded humidity profile, 4) mass of the rotor: measured (solid line) and from model prediction (dotted line), 5) rotor thickness (size)