Robust Control of a Gas Turbine with Wiener Model Uncertainty

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Abstract

The idea of robust control is employed to utilize a simpler Weiner model of a gas turbine instead of more complicated thermo dynamical models. Two sources of uncertainties are considered: (1) uncertainties due to nonlinear look-up tables in the Weiner model, which are obtained from experiments on the real engine, and (2) un-modeled dynamics which cannot be captured by the simple structure of the Wiener model. For simplicity, instead of the real engine experiments, a thermo dynamical non-linear model of the engine is considered. The frequency domain behavior of the Wiener model is compared with the nonlinear model and the observed deviations are considered as unknown uncertainties. Two robust controllers, using the well-known D-K iteration methods, are designed for the Wiener model under the presence of such uncertainties, which is then applied on the nonlinear model. Finally, for further investigations and introduction of more uncertainties, a real-time engine simulator is developed, which serves as a more uncertain system due to computational and communication time delays. Study of various time responses resulted by applying a set of step inputs with different magnitudes show that by design of a robust controller for simple Weiner's model of gas turbine, a better performance and robustness will be achieved in comparison with PID control methods. Besides, modeling and controller design have very simple structure in this method in contrast with complicated non-linear methods.

Keywords: Gas turbine, Weiner model, Robust control, Uncertainty, Modelica, Real time simulation

1. Introduction

Designing controllers which preserve the stability and provide a high level of performance during the whole operating map of the engine has attracted considerable attention during past decade (Giampaolo, 2006).

Several techniques have been put into practice to develop appropriate controllers for gas turbines. The well-known PID control strategy and various PID tuning control techniques such as the Ziegler-Nichols rule (Ziegler & Nichols, 1942), the no over-shoot rule of Seborg *et al.* (1989) and minimization of the absolute error integral by Pessen (1994) have been used extensively. Although the conventional methods are still being used mostly because of their simple structures and acceptable robustness in many industrial applications, Nonlinear nature and many un-modeled dynamics of the plant, in particular at the high frequency range, restrict the application of the engine near the surge line, a region where the engine works at the maximum efficiency. Gain-scheduling PID controllers have been used to improve the performance of conventional controllers. In order to overcome such difficulties, several techniques including the automatic tuning PID by Astrom and Hagglund (1984) and the rule-based auto-tuning of McCormack and Godfrey (1998), have been developed. However, due to use of linear and piece-wise linear models which did not include the unknown dynamics and nonlinearities, those methods were hard to tune optimally and did not lead to acceptable performance in the whole range of operations (Liu and Daley, 2001).

Various nonlinear control methods have been proposed for gas turbines. For example, the well-known 'model predictive control method' (MPC) has been extensively used for this purpose. The main idea of the MPC method has been mixed with a wide range of other control strategies, including the neural, fuzzy and adaptive control. The MPC method may exploit an adaptive model to predict the near future behavior of the process and compensate for the parameter variations of the plant. Van Essen and De Lange (2001), Brunell *et al.* (2002), and J. Mu *et al.* (2004) have proposed various MPC-based methods on gas turbines, although the resulting controllers have complicated structures and require a considerable computational time.

Due to potential characteristics of robust controllers in achievement of acceptable stability and performance for gas turbine, they have attracted considerable attention. As an illustration, Hyde (1995) developed an H_∞ loop-shaping design method for flight control applications. L. Gatley *et al.* (1999) developed an H_∞ loop-shaping for an integrated flight and propulsion control, to satisfy the engine safety limits.

In this paper, the idea of robust control method in the context of using the simpler Wiener model of a turbine, instead of extensive models or actual engines has been investigated. At first step, two different models are introduced for gas turbine. The Wiener model is a simplified first order system, with a speed-dependent time constant and a nonlinear gain which depends on the instantaneous operational condition of the real engine. In this study, the Wiener model is compared to a more extensive nonlinear model of the engine developed using the Modelica modeling language (Casella & Leva, 2003).

In order to design the robust controller for Weiner's model, the discrepancies between these two models are considered as an un-modeled dynamic uncertainty. Furthermore, the time constant and the nonlinear gain of Weiner model have been considered as parametric uncertainty of the model. Finally, the well-known D-K iteration method is used for design of the robust controllers. These controllers have been developed to satisfy both the performance robustness and the stability robustness. In particular, and at the first step, the parametric uncertainty of the Weiner model is considered and robust controller design is performed. Then, by considering both parametric and un-modeled dynamic uncertainties, a robust controller design is carried out. In addition, a PID controller is designed for the more extensive thermodynamic model using the 'Design Optimization toolbox' in Simulink.

In order to investigate the effectiveness of the designed robust controllers based on Weiner model, they are applied to Modelica model and various time responses are studied by applying a set of step inputs with different magnitudes. The results are compared to investigate the sufficiency of the robust controller that is designed base on Weiner's model in comparison with PID method by considering its simplicity.

Finally, In order to add even more uncertainty to the model of the plant, the designed controller with the best performance is applied to a gas turbine real time simulator through electronic I/O devices. This simulator serves as a more uncertain system, due to computational and communicational time delays. Plant responses to speed step inputs are compared for both non-real time and real time simulation to evaluate the performance of proposed controller.

2. Gas Turbine Modeling

2.1 Thermo dynamic model of gas turbine

In this approach, a thermo dynamical model of gas turbine is developed using Modelica programming language. This model has been assumed as the exact model of gas turbine due to the unavailability of a real one. Modelica takes advantage of DAE which consist of non-linear differential equations of unsteady power balance and algebraic aero-thermal equations of gas turbine. A schematic diagram of thermo dynamical non-linear model of gas turbine is represented in Fig. 1 that consists of its main components including compressor, combustion chamber, turbine, and joining pipes to connect the main components and consider the friction of gas flow. Inputs to the model are the fuel flow rate and physical parameters of the ambient air. The system output is arbitrary and can be rotor speed or any physical parameter in the entrance or existence of engine's components. This model has been assumed as the exact model of gas turbine due to the unavailability of a real one

This model has several advantages thanks to unique features of Modelica namely; high mathematical accuracy and the possibility of extending the model to a more complicated one by adding new components. Moreover, the model can be transported to MATLAB workspace and be used in the real time simulation (Casella & Leva, 2003). The model can be simulated over a working envelope from 4600 rpm to 5800 rpm. By transporting the model to MATLAB/ Simulink workspace, linearized models can be generated over the full operating envelope to study the frequency domain behavior of model.

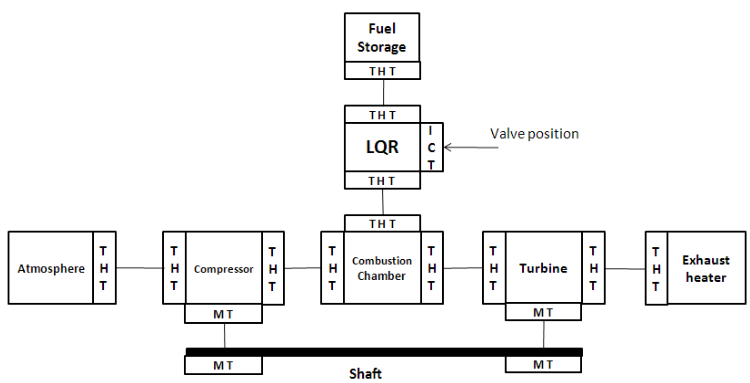
To illustrate the modeling approach, implementation of using Modelica in modeling the compressor is described briefly. Two characteristic equations in form of parametric terms are utilized to develop the compressor model by adding performance characteristics to a basic model of compressor. The basic model of compressor includes equations like balance of mass, balance of energy, and thermo dynamical equations of enthalpy. The performance characteristics are specified by two characteristic equations. The first relates flow number *Phic*, the pressure ratio *PR*, and referenced speed N_T; and the second one relates the efficiency *Eta*, *Phic* and N_T. To avoid singularity, *Phic*, *PR*, and *Eta* are calculated by aid of three tables and based on N_T and *Beta*. *Beta* is the number of arbitrary lines in performance map of compressor which are drawn parallel to surge lines (Casella & Leva, 2003).

$$phic = \frac{w}{\rho_i \Omega D} \quad (1)$$

$$N_T = 100 \times \frac{\Omega}{N_{design}} \times \sqrt{\frac{T_{idesign}}{T_i}} \quad (2)$$

$$Eta\ or\ \eta = \frac{h_{iso} - h_i}{h_o - h_i} \quad (3)$$

Fig.1. *Modelica model of Gas turbine (Flynn, 2003)*



2.2 Weiner Model of Gas Turbine

In the Wiener model (Kulikov &Thompson, 2004), the dynamical behavior of a gas turbine is approximated with a first order transfer function,

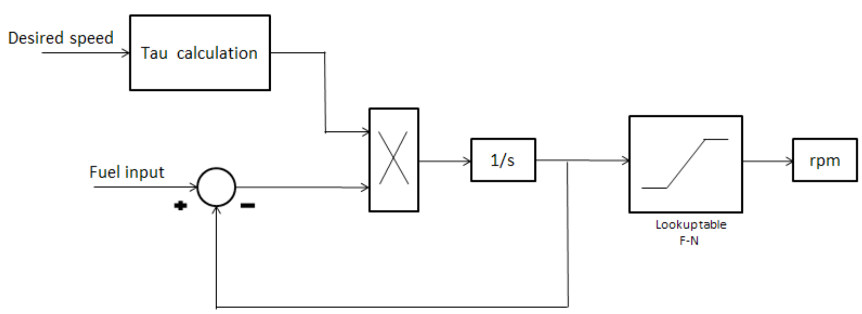
$$G(s)=A/(1+\tau s)+B \quad (4)$$

Here, is the time constant which is proportional to the inverse of the rotor speed and A is a nonlinear gain which depends on the operating condition of the engine. Furthermore, B is the residual error of the model. The schematic diagram of the Wiener model is illustrated in Fig. 2. The nonlinear gain, A, is obtained using some look-up tables which relate the fuel flow rate to the engine variables, and in particular to the rotor speed. The relative validity of the Wiener model has been verified by several experimental tests (Gold & Rosenzweig, 1952). The above mentioned table is usually constructed using the experimental tests on a real engine. In order to fix the idea, instead of using a real engine, the Modelica model is employed here, and simulations are performed around several working points. It turned out that the look-up table which relates the fuel flow to the rotor speed could be approximated by a straight line which can be defined as (2).

$$\omega = 1060.8\dot{m}_f + 2884.9 \quad (5)$$

In order to assess the validity of the Wiener model for the purpose of control design, simulations are carried out around various operating points. In order to capture the effects of the amplitude-dependent nonlinearities, small and large step inputs for fuel flow are applied at different operating conditions. Simulation results show similarities between the Modelica model and the simpler Wiener mode, as long as the amplitude of the step input is small enough. Larger step commands, however, lead to considerable discrepancies between the two models, as shown in Fig. 3.

Fig.2. *Weiner model of gas turbine*

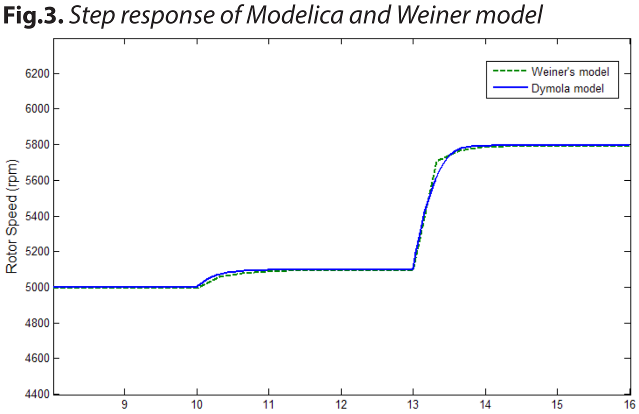


3. CONTROLLER DESIGN

3.1 Representation of uncertainty

Even the most accurate mathematical model of a real system cannot be more than an approximation of its real dynamics. There are several sources of uncertainty that may unfavorably influence the stability and performance of the control system, which can be categorized as parametric and unknown uncertainties (Skogestad & Postlethwaite, 1996).

Fig.3. *Step response of Modelica and Weiner model*



In the Weiner model, the time constant in (4) is considered as the parameter of the system which varies in accordance with the defined operating points. Change of rotor speed across the operating map, will vary the time constant from 2.95s to 3.75s (This is obtained by extensive simulations on the Wiener model and comparison with the thermo dynamical model). Therefore, parametric uncertainty can be represented mathematically as following:

$$\tau = \bar{\tau}(1 + P_\tau \delta_\tau) = 3.35 \quad (6)$$

$$P_\tau = \frac{\tau_{max} - \tau_{min}}{\tau_{max} + \tau_{min}} = 0.119 \quad (7)$$

$P_\tau = 0.119$, i.e., 11.9% uncertainty for the time constant. Here, M_τ is defined as

$$M_\tau = \begin{bmatrix} -P_\tau & a/\bar{\tau} \\ -P_\tau & a/\bar{\tau} \end{bmatrix} \quad (8)$$

The other source of perturbation that may affect the performance of gas turbine control system is resulted from missing dynamics in modeling the real system. Any model of a real system contains this kind of uncertainty and while it is less precise than parametric uncertainty, it is mostly considered as a complex perturbation that is normalized as $\|\Delta\|_\infty < 1$. Δ is any stable transfer function that is less than one at each frequency range. In the case of robust controller design for Weiner model, use of a first order transfer function for modeling the engine causes inaccuracy particularly in high frequencies while the exact model of engine should be defined by a higher order non-linear transfer function.

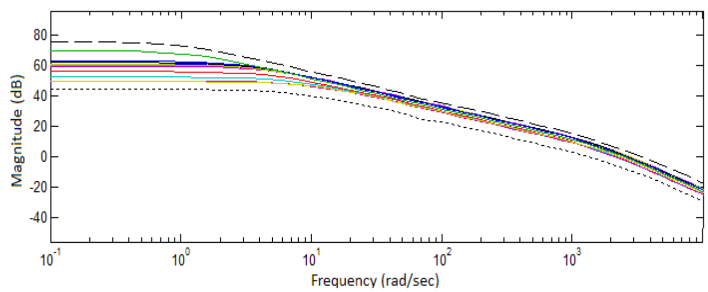
As mentioned earlier, the thermo dynamical model developed by Modelica is assumed as the exact model of gas turbine. Following steps have been carried out in order to drive the un-modeled weighting function, $W_i(s)$, which illustrates the shape of unknown uncertainties.

- In order to investigate its frequency domain behavior, the nonlinear Modelica model has been transformed into a Simulink block, and linearized around several operating points across the operating envelope. Linearization has been performed by the aid of Simulink routine *Linmod* and by considering the fuel flow rate as input of system which changes in 0.1 kg/s steps from 1.142 to 2.92 kg/s. The rotor speed is considered as the output of this SISO system.
- To obtain an uncertainty bound compared with the central non-linear model, the frequency response plots of the Modelica model for the above range of transfer functions are plotted, as shown in Fig. 4. Two transfer functions called N_l and N_u are obtained, as the approximation of upper and lower bounds of the responses. In addition, the lower and upper uncertainty bounds of the Wiener model, namely, U_b and L_b are determined using and Finally, (5) is used to derive the appropriate weighting function of un-modeled dynamic uncertain-

ty, in which $G_p(s)$ is the perturbed model, i.e., the Modelica model and G(s) is the nominal plant, i.e., the Weiner model. Here, $L_i(s)$ represents the relative difference between these two plants. The suitable weighting function is the one that is slightly larger than the supremum of $L_i(s)$ in the whole range of frequencies.

Over all configuration of Weiner model of gas turbine including uncertainty is shown in Fig. 5, in which both parametric and dynamic uncertainties have been taken into account. These two sources of uncertainty can be extracted from the nominal plant be considered as a single uncertainty block known as structured uncertainty.

Fig.4. *Uncertainty bounds of Modelica model in the frequency domain; "---"N_u and "..."N_l*



$$L_i(s) = \left|\frac{G_p(s) - G(s)}{G(S)}\right| \tag{9}$$

$$W_i(s) > \max L_i\left\{\left|\frac{U_b - N_i}{N_i}\right| \ and \ \left|\frac{L_b - N_u}{N_u}\right|\right\} \ for\ all\ \forall\omega \tag{10}$$

3.2 Design specifications

In this study, core speed control of gas turbine has been probed and Functional specifications for the control system are given as follows.

- The robust controller should guarantee the robust stability of the gas turbine that means the closed-loop system must remain stable in presence of all possible uncertainties. In order to secure the suitable robust stability, complimentary sensitivity function (T) has been used. According to Kulikov and Thompson (2004), the robust stability for a system with multiplicative input uncertainty is as equation (7).

$$RS \overset{equal\ with}{\Longleftrightarrow} \|W_i(i\omega)T(i\omega)\|_\infty \le 1 \ \ for\ \forall\omega \tag{11}$$

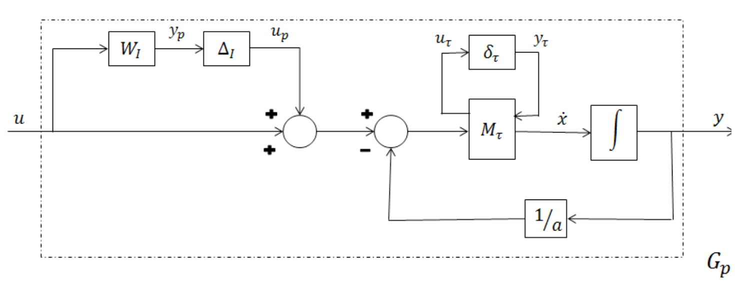


Fig.5. *Plant including parametric and un-modeled dynamic uncertainty*

- During the design procedure, relatively fast responses and small over shoots can be assumed as suitable performances of gas turbine. Consequently, acquiring the nominal performance and robust performance for gas turbine, is another crucial factor that should be fulfilled by designed controller. To ensure this, the sensitivity function (S), has been used. A sufficient small magnitude of S in specific frequency ranges can satisfy precise performance characteristics. According to the MathWorks, Inc., all these characteristics can be obtained by defining a performance weighting function, $W_p(s)$, which is used to shape the sensitivity function.

$$NP \overset{equal\ with}{\Longleftrightarrow} \|W_p(i\omega)S(i\omega)\|_\infty \le 1 \ \ for\ \forall\omega \tag{12}$$

In the case of robust performance, S_p (perturbed sensitivity) should be utilized instead of S. Therefore, we have the following equation.

$$RP \overset{equal\ with}{\Longleftrightarrow} \|W_p(i\omega)S_p(i\omega)\|_\infty$$

$$\le 1 \overset{equal\ with}{\Longleftrightarrow} \|W_p(i\omega)S(i\omega)\|_\infty + \|W_i(i\omega)T(i\omega)\|_\infty \le 1 \tag{13}$$

3.3 Robust controller design

In order to assure the achievement of robust stability and robust performance, design method based on the structural singular value (μ) can be used. For complex uncertainties, as in our case, D-K iteration method is an appropriate method that is resulted from the combination of H_∞ synthesis and μ analysis. While the gas turbine controller should satisfy several specifications, a mixed sensitivity H_∞ design with following mixed sensitivity problem should be solved. This method is extensively clarified in reference (Skogestad & Postlethwaite, 1996; Gu *et al.* 2005).

$$\left\|\begin{bmatrix} W_p(I+GK)^{-1} \\ W_u K(I+GK)^{-1}\end{bmatrix}\right\|_\infty \le 1 \tag{14}$$

This control design procedure consists of two main stages. First, the open-loop plant is shaped by $W_p(s)$ to move the singular values of open-loop frequency response to desired places. The primary guess for this weighting function is obtained by information given by reference (Skogestad & Postlethwaite, 1996) that is based on the available information about the system behavior and the desired response. In this case, a $W_p(s)$ of second order will satisfy the expected robust performances and stability. In the next step, D-K iteration method is performed to robustly stabilize the closed-loop plant. In this method, for an optimal robust stability and performance design, the objective is to minimize the following mathematical statement.

$$\inf\sup \mu[N(P,K)(j\omega)] \tag{15}$$

N is derived using N-Δ structure and is the nominal closed-loop interconnected transfer function matrix not including the perturbation. To solve the controller design problem, an upper bound will be considered for μ as it is shown in (12).

$$\mu[N(P,K)(j\omega)] \le min\bar{\sigma}\,(DND^{-1})(j\omega) = \gamma \quad , for\ \forall\omega \tag{16}$$

In this equation, D is the scaling diagonal matrix used to find a tighter bound for μ. The design will be carried out during an iterative problem in which D or K changes while the other one is fixed. The iteration stops when the H_∞ norm of DND^{-1} becomes less than one or does not diminish anymore. If the resultant value of μ is more than one, the chosen weighting function is incompatible with robust stability and an iterative redesign of the function is required.

In this investigation, D-K iteration method is carried out for two different cases. First, it is performed while only the parametric uncertainty has been applied to the plant. Then, un-modeled dynamic uncertainty is added to the model and the control design procedure has been repeated for Weiner model including structured uncertainty.

In addition to robust controllers, a simple PID controller is designed for Modelica model of gas turbine. Responses to various step inputs obtained from applying the PID controller to the thermo dynamic model of engine will be compared with responses of designed robust controllers to discover their competences. "Simulink Design Optimization toolbox" of MATLAB is utilized to design the PID controller. In this toolbox, controller can be refined by optimizing its parameters in SISO design tool.

$K_{p\text{-}dk}$ specifies the controller designed for the plant including only the parametric uncertainty and the one achieved for plant with structured uncertainty is indicated as $K_{s\text{-}dk}$. Difference in definition of uncertainty in these two cases leads to various performance weighting functions.

By implementing DK-iteration method on both plants, $K_{p\text{-}dk}$ achieves suitable stability after three iterations and the peak Mu value reaches 0.740. In the case of $K_{s\text{-}dk}$, γ that is less than one will be achieved after four iterations and it would be equal to 0.8396. Both $K_{p\text{-}dk}$ from order 9 and $K_{s\text{-}dk}$ from order 18 are stable transfer functions; however, the order of $K_{s\text{-}dk}$ is reduced to 9 using Hankel norm approximation method. The controller order is lessened to diminish the calculation time while this reduction does not have considerable effects on system behavior as it is shown in Fig. 6.

In order to analyze the robust characteristics of controllers, Mu synthesis is utilized for both controllers. Mu function of MATLAB computes upper and lower bounds of the structured singular value for related systems with respect to uncertainty blocks. The M-Δ structure is used to probe the robust stability and to provide it; $\mu(M) < 1$ must be gained. Furthermore, in the purpose of investigating the robust performance the N-Δ structure is used. In this case, $\mu(N) < 1$ should be fulfilled (Skogestad & Postlethwaite, 1996). The frequency responses of μ showing the nominal performance (NP), robust performance (RP), and robust stability (RS) of $K_{p\text{-}dk}$, $K_{s\text{-}dk}$, and PID controller are given in Fig. 7 to Fig. 9. From Fig. 7 and Fig. 8, it is obvious that NP, RS, and RP are satisfied for both robust controllers. However, they may reach close to the unity in some frequencies for $K_{s\text{-}dk}$ controller due to applying a complex un-modeled dynamic uncertainty to a simple first order Weiner model. PID controller is not capable of obtaining RP and RS in a wide frequency range while they exceed unity as it is shown in Fig 9.

3.4 Comparison of $K_{p\text{-}dk}$, $K_{s\text{-}dk}$, and PID controllers

Responses to randomly selected step inputs for the non-linear Weiner model, with the $K_{p\text{-}dk}$, $K_{s\text{-}dk}$, and PID controller are compared in Fig. 10 and Fig. 11. The control system with $K_{p\text{-}dk}$ illustrates the best performance with almost no overshoot and very small rise time.

Fig.6. *Comparison of exact Ks-dk and the reduced Ks-dk*

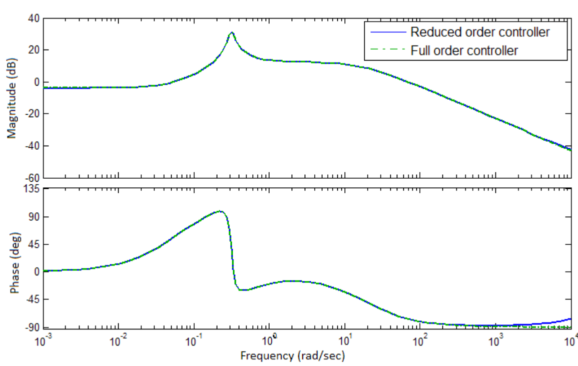


Fig.7. *NP, RS, RP for Kp-dk*

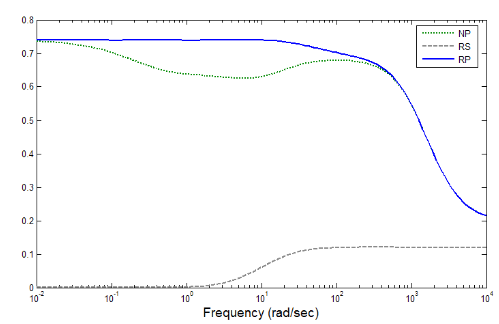


Fig.8. *NP, RS, RP for $K_{s\text{-}dk}$*

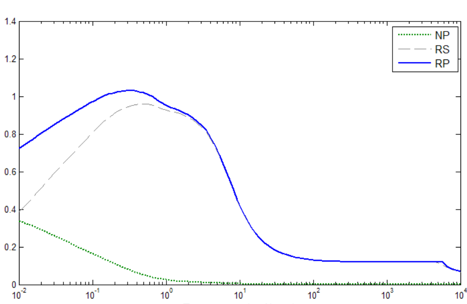
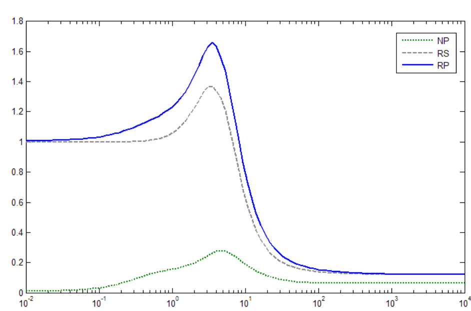


Fig.9. *NP, RS, RP for PID controller*



However, $K_{s\text{-}dk}$ depicts the weakest performance with more than 30% overshoot when complex external perturbations are added to the simple first-order Weiner model during the controller design. Therefore, $K_{s\text{-}dk}$ turns out to be more conservative for this simple model and will not satisfy the desired control objectives.

Fig.10. *Step response of nonlinear Weiner model including $K_{p\text{-}dk}$, $K_{s\text{-}dk}$, and PID controller*

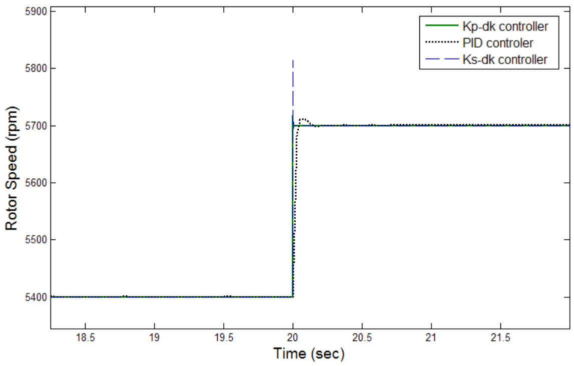
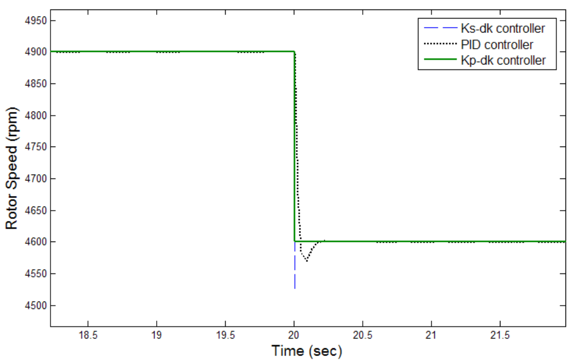


Fig.11. *Step response of nonlinear Weiner model including $K_{p\text{-}dk}$, $K_{s\text{-}dk}$, and PID controller*



To validate the performance and proficiency of designed controllers, they are applied to an extensive thermodynamic model of the gas turbine. For this purpose, several randomly selected step inputs are applied to the model. As it was expected, $K_{p\text{-}dk}$ controller which is designed in presence of parametric uncertainties of Weiner's model achieves the best performance with respect to small steps because they mostly stimulate linear modes of the Modelica model (see Fig. 12). However, in the case of large fuel step inputs which provoke the nonlinear modes of engine, performance of $K_{p\text{-}dk}$ degrades, for un-modeled dynamic uncertainty that is related to the nonlinearity of exact model is not included in this controller. In this case, $K_{s\text{-}dk}$ provides a better performance with almost no overshoot and a relatively small raise time as shown in Fig. 13. However, it does not obtain a suitable settling time yet. In summary, although $K_{p\text{-}dk}$ faces some overshoots for large inputs, its performance still remains acceptable; therefore, it can be used as an appropriate controller for the complex model in all frequency ranges. As it is obvious from Fig 12 and Fig 13, the PID controller depicts the highest overshoot for both small and large inputs. This is because; it is designed for a linearized model around a particular operating point.

Fig.12. *Small magnitude closed-loop step response of Modelica model*

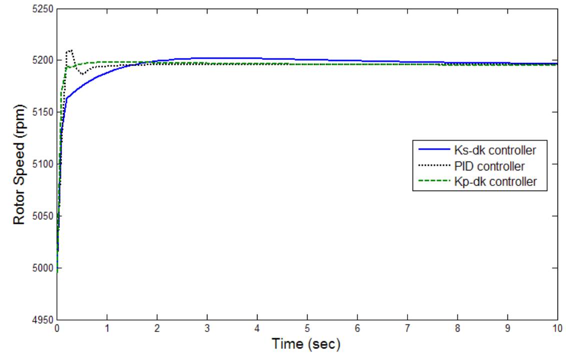
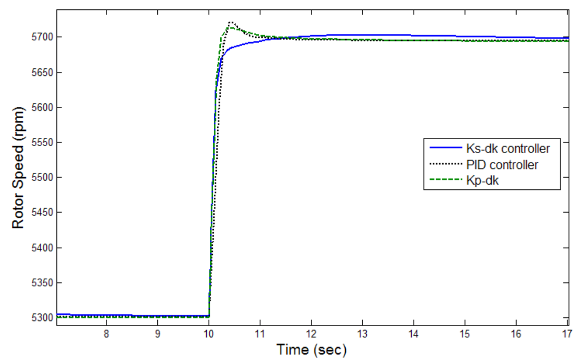


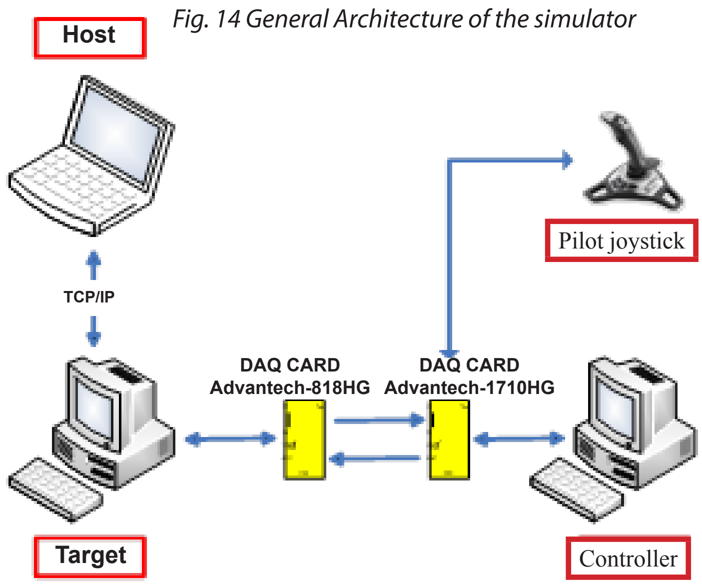
Fig.13. *Large magnitude closed-loop step response of Modelica mode*



4. IMPLEMENTATION OF ROBUST CONTROLLER ON GAS TURBINE REAL TIME SIMULATOR

To show the robustness of the best performance designed controller, $K_{p\text{-}dk}$, it has been applied to a gas turbine real time simulator which adds more uncertainty to the plant due to computational and communicational time delays. Architecture of the simulator framework for real time implementation and hardware control of a generic system is depicted in Fig. 14. The system and the controller communicate each other through data acquisitions cards. The process has different stages namely; real time simulation, GUI design, and network communications. These stages are discussed with more details in the following sections.

Fig. 14 General Architecture of the simulator



4.1 Real time simulation

Real time simulation of the gas turbine system is carried out in xPC target environment of MATLAB/SIMULINK software which uses host and target architecture (The MathWorks, Inc.). In this architecture Host computer, on which MATLAB software is installed, converted a SIMULINK model to an *Application* program with Real Time Workshop and C/C++ compiler. Then the application program is loaded on another computer which is called Target computer. The target computer doesn't need any special operating system and is run with the xPC Target Kernel.

After loading the application program on the target computer, this program is run in a real time manner with the xPC target kernel. Though the application program can be run very fast, model complexity and power of target computer hardware reduce the sampling frequency.

To implement host/target architecture, the Modelica model is exported to SIMULINK software in the form of a block with specified inputs and outputs. After compiling the block in xPC target environment the application program of the model (Model.dlm) is created. The application program is then loaded on the target computer through a program written in the C# programming language. In addition, another file (Model.dll) is generated through xPC Target COM API module. This file can be used by the C# program to change model parameters during real time simulation.

4.2 Graphical Interface Design

A GUI is designed in Advantech Studio software in order to (1) set/ change the model parameters and to (2) monitor different locations of the engine. Model parameters, simulation initial conditions can be set/ changed via virtual elements of the designed GUI. Moreover, graphs related to changes of temperature, pressure, and flow rate sensors which are installed in different positions of the engine such as turbine, compressor, and combustion chamber are illustrated in the GUI. Moreover, Advantech Studio monitoring software can interact with DAQ cards, input parameters can be applied physically and values of sensors can be shown in physical/ real apparatus.

4.3 Communication Protocols of the gas turbine Simulator

A program written in C# programming language, manage the network communications and data transfer between different parts of the simulator. Specifically the C# application performs the following tasks through TCP/IP protocol;

- Downloading the application model generated in Simulink on the Target computer
- Starting and stopping of the simulation
- Data transfer between the target computer (the gas turbine real time model) and the host computer (the control and monitoring GUI)

Additionally, using the C# program, the GUI and the gas turbine model are connected to each other on the host computer. However, this connection is established through OPC protocol. Besides the host computer, the target computer is connected to another computer, loaded by the designed controllers, through two DAQ cards. Some sample results of the simulator is shown in Fig. 15. Results are drawn for the closed-loop system including $K_{p\text{-}dk}$ controller which is commanded by a desired turbine shaft speed. In this figure changes of temperature, pressure, input turbine flow rate, and rotational speed are shown.

Plant responses to speed step inputs are compared for both non-real time and real time simulation in Fig. 16. Although the real time simulation faces some oscillations in its response due to the use of DAQ cards, it has acceptable similarity with non-real time simulation. It can be cited that the designed robust controller for the simple model of Weiner ($K_{p\text{-}dk}$), by considering only parametric uncertainty of it, remains robust in presence of uncertainties resulted from real time simulation. However, performing the real time simulation with smaller sample times would lead to diminish the oscillations; however, it requires CPU with higher processing capability.

Fig.15. *Online trend of gas turbine properties*

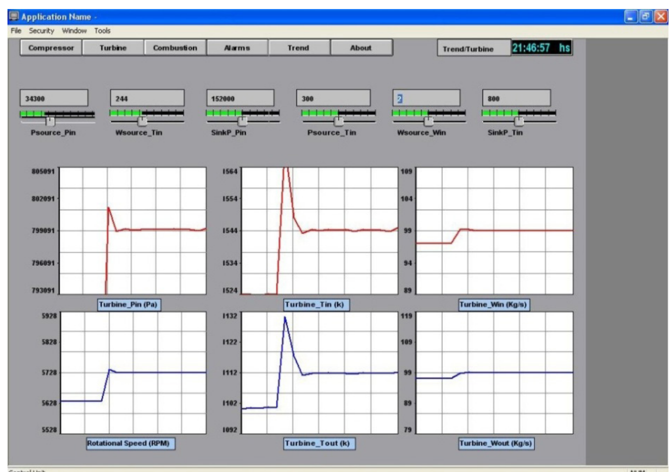
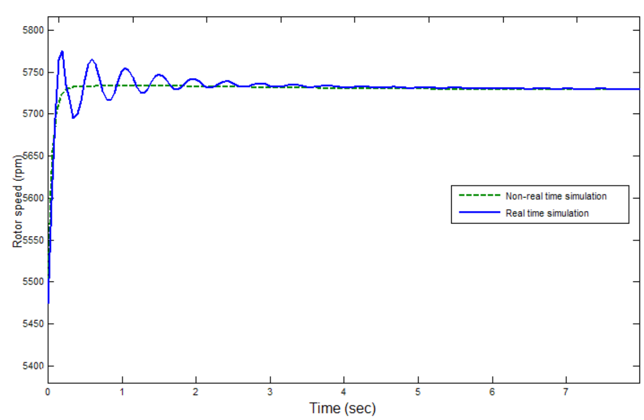


Fig.16. *Comparison of real time and non-real time simulation*



5. CONCLUSION

This paper can be divided into two parts. In the first part, a robust controller design is performed for a simpler model of gas turbine developed by Weiner modeling approach. Two sources of uncertainty are considered. At first, only parametric uncertainty resulted from the time variant parameter of Weiner model is used to design the controller. Then, un-known dynamic uncertainty derived due to the differences between frequency domain behavior of Weiner model and fairly exact, thermo dynamical model of gas turbine, is added to the plant and robust design procedure is repeated for structured uncertainty. In addition, a PID controller is developed to be compared with robust controllers. Non-linear simulations show that the robust controller which is designed by only considering parametric uncertainty of Weiner model represents suitable performances over the full operating envelope. In second part, a design process and implementation framework of a gas turbine simulator is developed for the complex model of gas turbine including the designed controller to probe the robustness of controller in real time simulation. Results of Simulations represent good tracking of real time response in comparison with simulation without time limitations. The results depicted in this paper show that by design of a robust controller for simple Weiner's model of gas turbine, a better performance and robustness will be achieved in comparison with PID control methods. In addition, modeling and controller design have very simple structure and calculation algorithm in contrast with complicated non-linear methods.

Further work will involve development of the Modelica model of gas turbine to acquire more exact uncertainties which can be performed by adding supplementary components like inlet fan and air by pass ducts. While the discrepancies between frequency domain behaviors of Weiner's model and thermodynamic model are considered as unknown uncertainties, applying improvements to the Modelica model leads to achievement of more precise un-modeled uncertainties and controllers.

Implementing the safe control of gas turbine in the real-time simulation is another investigation which should be carried out regarding the plausible conservative behavior of robust controllers, particularly while engine is operating near its working limits.

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7. APPENDIX

Nomenclature

Beta = Number of surge lines

D = Mean diameter of wheel

Eta = Efficiency

G(s) = Nominal plant

$G_p(s)$ = Perturbed plant

h_i = Enthalpy of entrance gas

h_{iso} = Enthalpy of discharging gas from isentropic compressor

h_o = Enthalpy of discharging gas

$\dot{m}_f$ = Fuel flow

N_T = Referenced speed

Phic = Flow number

PR = Pressure ratio

P_τ = Related parametric uncertainty

S(s) = Sensitivity function

T_i = Temperature of entrance gas

T(s) = Complementary sensitivity function

w = Mass flow rate

$W_i(s)$ = Un-modeled weighting function

$W_p(s)$ = Performance weighting function

ρ_i = density of entrance gas

Ω = Rotor speed

τ = Time constant

ω = Rotor speed

δ_τ = Parametric uncertainty

Δ = Complex perturbation