7. ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2013-051**
11-13 September 2013 - METU, Ankara TURKEY

ADAPTIVE SLIDING MODE CONTROLLER DESIGN OF A TURBOSHAFT ENGINE

Erkan Abdulhamitbilal*
ISTAVIA Engineering
Istanbul, Turkey

ABSTRACT

In this study, an adaptive sliding mode controller is designed for stabilization of a turboshaft engine. Engine dynamics are addressed with variation of gas generator speed as driven by a manufacturer. An adaptive sliding mode control algorithm is designed for considered engine dynamics. Proposed control algorithm is simulated and compared with PI control law supplied by FADEC of engine. The proposed adaptive sliding mode control law is simple and easy to be implemented into real-time on-board computer. Simulation results show effectiveness of proposed control algorithm.

INTRODUCTION

A turboshaft engine (see Figure 1) is made up of two major part assemblies: the "gas generator" and the "power section". The gas generator consist of the compressor, combustion chambers with ignitors and fuel nozzles, and one or more stages of turbine. The power section consists of additional stages of turbines, a gear reduction system, and the shaft output. The gas generator creates the hot expanding gases to drive the power section. Depending on the design, the engine accessories may be driven either by the gas generator or by the power section.

Figure 1: A Turbomeca turboshaft engine

*Researcher, Email: abdulhamit@itu.edu.tr

Full Authority Digital Engine Control (FADEC) is a system consisting of digital computer, called and electronic engine controller or engine control unit which controls all aspects of engine performance. FADECs have been produced for piston engines, jet engines, turboshaft engines, etc. Engine performance is critical to airframe control because of the dependence on constant rotor speed under varying loads.

Sliding mode control has a wide area of use in aviation, automotive, chemical, oil, etc. industries. The theory of sliding mode is well evaluated in [Utkin, 1992; Hung, 1993], etc. Deeply investigation of small turboshaft engines and mathematical models are done in [Ballin, 1988; Duyar, Gu, and Litt, 1995], etc. A control system sturctures of a turboshaft engine is studied in [Abdulhamitbilal, 2010; Spack, 2011], etc. The validated mathematical model of considered turboshaft engine is supplied by its manufacturer [Turbomeca[1], 2006]. It is a prospect that engine data is obtained from several test results operated by manufacturer. All properties, specification, operation and installation guide of the considered turboshaft engine is included [Turbomeca[2], 2006].

This study attempts to quantify faster and adaptive torque control system for a turboshaft engine. Sliding mode control theory is considered to achieve faster and robust results to bounded disturbance and unmodeled dynamics. Implimentation of control algorithm on a real-time electronic engine controller is easy and cost effective. Improvement of control performance of turboshaft engine also affects the performance of maneuverability and stability of the aircraft/rotorcraft.

What follows is introduction of parametrci engine dynamics with gas generator speed and design of an adaptive sliding mode controller. Proposed architecture and manufacturer algorithm are simulated and compared. A conclusion finilizes the study.

TURBOSHAFT ENGINE DYNAMICS

Consider the following linear turbo-shaft engine dynamics in parametric form of gas generator speed, $N1$, as [Abdulhamitbilal, 2010]:

$$\begin{aligned} \dot{x}(t) &= A(N1)x(t) + B(N1)u(t) \\ y(t) &= C(N1)x(t) + D(N1)u(t) + E(N1)\nu(t) \end{aligned} \tag{1}$$

where state $x(t) = dN1$ is gas generator variation, and output $y(t) = dT$ is torque variation of engine gear box output shaft. The

$$A(N1) = -\frac{dC_H}{dN1}\frac{dCG}{dC_H}k_{NG} \tag{2}$$

$$B(N1) = \frac{dCG}{dC_H}k_{NG} \tag{3}$$

$$C(N1) = \frac{dT}{dN1} - \frac{dC_H}{dN1}\frac{dT}{dC_H} \tag{4}$$

$$D(N1) = \frac{dT}{dC_H} \tag{5}$$

$$E(N1) = \frac{dT}{dN2} \tag{6}$$

$$k_{NG} = \frac{60000}{2\pi NG_{NOM} I_G} \tag{7}$$

Also, $I_G = 0.0138kgm^2$ is gas generator inertia and $NG_{NOM} = 54117t/mn$ is gas generator nominal speed. Note that, C_H is fuel flow and dC_H is fuel flow variation; $N2$ is power turbine speed; and NR is rotor speed. Table 1 gives the parameters which construct linear dynamic system with respect to $N1(\%)$.

SLIDING MODE CONTROLLER DESIGN

The trajectories of turbo-shaft engine (1) can be constrained in finite time to reach and stay onto a sliding surface subject to control law:

$$u = \begin{cases} u^+ & \text{if } s > 0 \\ u^- & \text{if } s < 0 \end{cases} \tag{8}$$

Table 1: Linear parameters of a turbo-shaft engine [Abdulhamitbilal, 2010]

$N1$ $\%$	$\frac{dCG}{dC_H}$ $\frac{mdaN}{(l/h)}$	$\frac{dC_H}{dN1}$ $\frac{(l/h)}{\%N1}$	$\frac{dT}{dC_H}$ $\frac{mdaN}{(l/h)}$	$\frac{dT}{dN1}$ $\frac{mdaN}{\%N1}$	$\frac{dT}{dN2}$ $\frac{mdaN}{\%N2}$
90.5446	0.0362	6.3587	0.2589	3.6800	-0.4104
99.7838	0.0304	10.1469	0.2461	5.1005	-0.5142
110.8709	0.0202	11.4728	0.2235	3.1636	-0.5916

where s represents sliding manifold defined for parametric linear systems (1) [Utkin, 1992; Hung, 1993]:

$$s(t, N1) = C(t, N1)x(t) \tag{9}$$

If we take the derivaive of sliding function in substitude (1) into (9), we can describe the sliding motion as:

$$\begin{aligned} \dot{s}(t, N1) = & C(t, N1)A(t, N1)x(t) \\ & + C(N1)B(N1)u(t, N1) \end{aligned} \tag{10}$$

If $C(N1)B(N1)$ is invertible then equivalent control can be written as:

$$u_{eq}(t, N1) = -(C(N1)B(N1))^{-1}[C(N1)A(N1)x(t)] \tag{11}$$

Existence of sliding motion depends on the deviations from sliding surface. Its time derivative should have opposite sign in the neighborhood of switching surface $s(t, N1) = 0$, [Utkin, 1992]:

$$\lim_{s \to +0} \dot{s} < 0 \quad and \quad \lim_{s \to -0} \dot{s} > 0 \tag{12}$$

Hence the control law can be constructed as equivalent term to stabilize the engine dynamics for variation of $N1$.

$$u(t, N1) = u_{eq}(t, N1) \tag{13}$$

COMPARISON ANALYSIS

A turboshaft engine was shipped from Turbomeca under a research project for design and manufacturing a prototype helicopter by Istanbul Technical University. The engine can produce 690 shaft horse power and $820Nm$ torque at $6000rpm$ at engine gearbox output. The control law in FADEC is PI control. The performances of Engine and FADEC are satisfactory. However after performing some simulation on mathematical model of the engine supplied by manufacturer I have seen that time responses reach equilibrium in 9 seconds, which can be improved. From this point of view I have developed and proposed an adaptive sliding mode controller in previous section to improve performances and settling time of system trajectories.

The block diagram of a complete helicopter with the turboshaft engine connected to gear box and rotor is given in Figure 2. The aim in this study is elimination of $1000Nm$ external torque on main rotor. Manufacturer and proposed control algorithms are examined and compared as follows. After running simulation for 10 seconds for$N1$ @ 100% at sea level the time responses are calculated for rotor torque variation in Figure 3, gas generator speed in Figure 4, gas generator speed variation in Figure 5, and fuel flow in Figure 6. Note that C_H is control input of engine. The proposed adaptive sliding mode control algorithm results are illustrated at left side, and PI control algorithm results are shown at right side.

As seen from simulation results the adaptive sliding mode controller stabilizes the dynamic system in 2-3 seconds. On the other hand, PI controller stabilizes in 9 seconds. which is approximately 4 times longer then sliding mode controller. Proposed control algorithms do not have any overshoots and uses fuel effectively. Proposed control algorithm reduces fuel consumption which reduces CO_2 emission. Therefore proposed control law is more green then manufacturer's one.

CONCLUSION

Turboshaft engine systems are an important class of engines which are often used for helicopter propulsion. Control of these engines takes important topic in control system engineering. An adaptive sliding mode control system architecture is proposed for faster stabilization and reduction of fuel consumption for a turboshaft engine. The control system architectures is compared and simulated with supplied PI control algorithm by manufacturer. Results show effectiveness of proposed control algorithm which is robust with respect to parametric uncertainties and disturbances.

References

V.I. Utkin (1992) *Sliding Modes in Control Optimization*, Springer-Verlag, Berlin

J.Y. Hung (1993) *Variable structure control: a survey*, IEEE Transactions on Industrial Electronics, Vol 40, pp. 2-22

M.G.Ballin (1988) *A high fidelity real-time simulation of a small turboshaft engine*, NASA TM 100991

A.Duyar, Z. Gu, J. S. Litt (1995) *A simplified dynamic model of the T700 turboshaft engine*, Journal of American Helicopter Society, vol. 40, pp. 62-70

E. Abdulhamitbilal (2010) *ITU-Light Commercial Helicopter Flight Dynamics, Stability Analysis, and Interconnected Control Systems Design*, PhD Thesis supervised by Prof. E.M.Jafarov, ITU-Library, Istanbul

J.M. Spack (2011) *Linear parameter varying controller for a small turboshaft engine*, MSc Thesis, Northeastern University, Boston, Massachusetts

Turbomeca (Groupe SAFRAN) (2006) *NT Arrius 2T Linear Model Description, Note Technique, AA006482 Version A*, Bordes Cedex, France.

Turbomeca (Groupe SAFRAN) (2006) *Installation / Operation Manual*, Bordes Cedex, France.

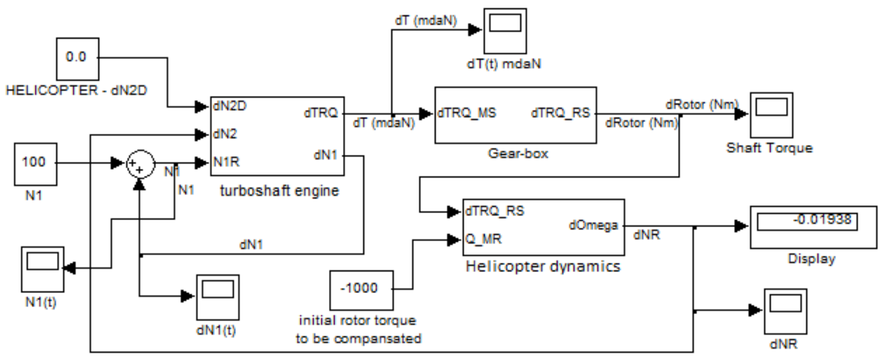
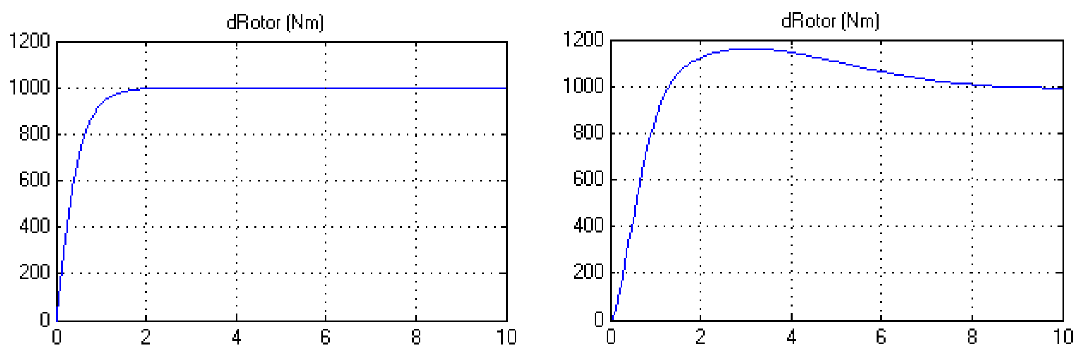
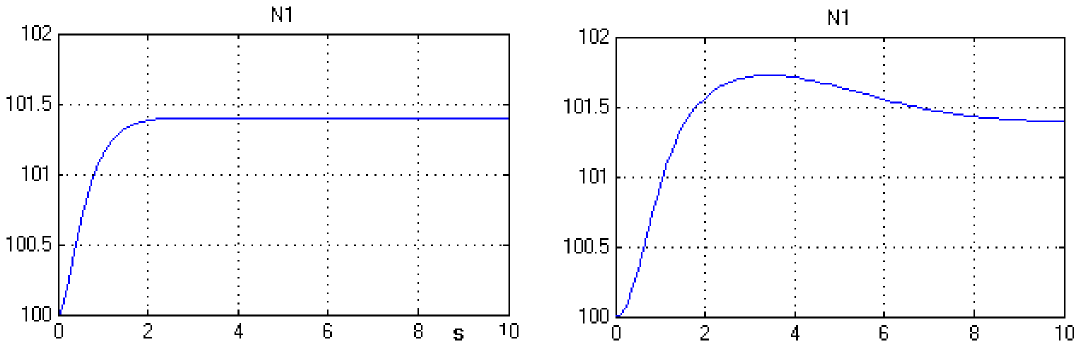


Figure 2: Matlab-Simulink block diagram turboshaft engine - helicopter system



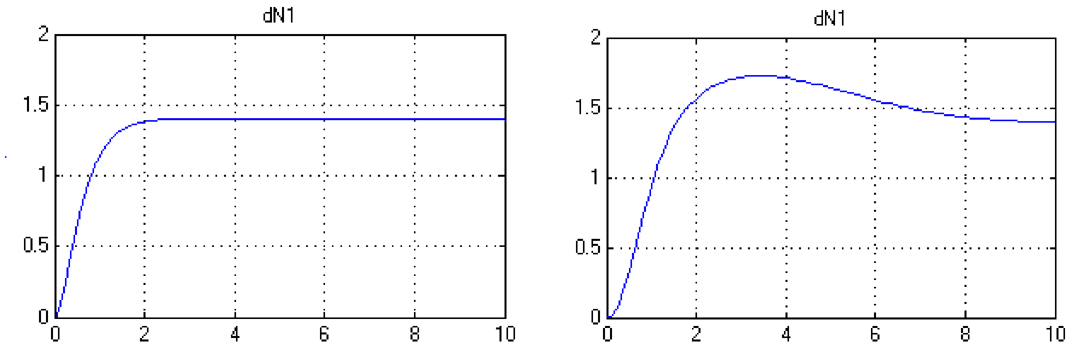
(a) equivalent control (b) PI control

Figure 3: Rotor torque



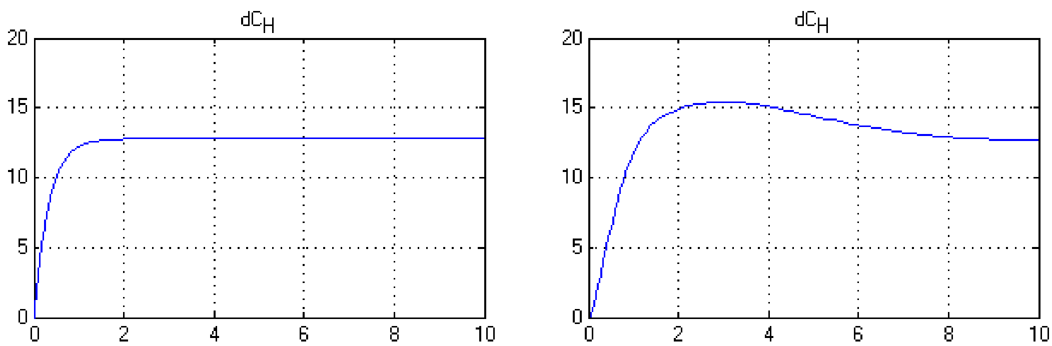
(a) equivalent control (b) PI control

Figure 4: Gas generator speed, $N1$



(a) equivalent control (b) PI control

Figure 5: Gas generator speed variation $dN1$



(a) equivalent control (b) PI control

Figure 6: Control parameter: fuel flow, C_H