High-Order Sliding Mode Control of a Turboshaft Engine

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***Abstract*—In this study, a turboshaft engine performance is improved by design of high orders sliding mode controller. Engine dynamics are addressed with variation of gas generator speed as driven by the manufacturer. Proposed controller is designed to cover all parametric variations of the engine. Successful simulations have been performed to illustrate the effectiveness of the proposed solution technique.**

I. INTRODUCTION

A turboshaft engine (see Fig. 1) may be made up of two major parts assemblies: the 'gas generator' and the 'power section'. The gas generator consists 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.

Full Authority Digital Engine Control (FADEC) is a system consisting of digital computer, called an electronic engine controller or engine control unit which controls all aspects of aircraft engine performance. FADECs have been produced for piston engines, jet engines, tuboshaft engines, etc.

Engine performance is critical to airframe control because of the dependence on constant rotor speed under varying loads for rotorcrafts. This study attempts to quantify faster, adaptive and robust torque control system for a turboshaft engines with high orders sliding mode control approach.

Variable structure control (VSC) has a wide area of use in aviation, automotive, chemical, oil, etc. industry. The theory of high order sliding mode, which is a sub topic of VSC, is well evaluated in [1]. A valuable discussion on high order sliding mode and comparison with conventional sliding mode control is studied in [2]. A high fidelity real-time simulation of a small turboshaft engine is studied and result are reported in [3]. A simplified dynamic model of T700 turboshaft engine is driven in state space and some simulation for different operating regimes are performed in [4]. Full nonlinear mathematical model of a light commercial helicopter, where turboshaft engine dynamics are driven, advances of rotorcraft analysis and modeling with interconnected control systems design is studied in [5]. A linear parameter varying controller for a small turboshaft engine is designed and simulated in [6]. Aeronautical design standards on handling qualities for military helicopters are addressed in [7].

A turboshaft engine was shipped from an European manufacturer under a research project to design and manufacture a prototype helicopter. The engine can produce 690 shaft horse power and 820 Nm torque at 6000 rpm at engine gearbox output. The feedback law in FADEC is PI based controller. The performances supplied by manufacturer of Engine and FADEC are satisfactory. However after performing some analyzes and simulations it is observed that time responses reach equilibrium in 9 seconds. This performance may not be satisfactory under consideration of handling qualities and agile maneuvering [7]. Due to these motivations, this study aims to improve performances and settling time of system trajectories of a turboshaft engine for agile maneuvering under disturbative torques on main rotor with high-order sliding mode control techniques.

What follows is introduction of parametric engine dynamics with gas generator speed and design of a high order sliding mode controller. Proposed architecture and manufacturer algorithm are simulated and compared. A conclusion finalizes the study.

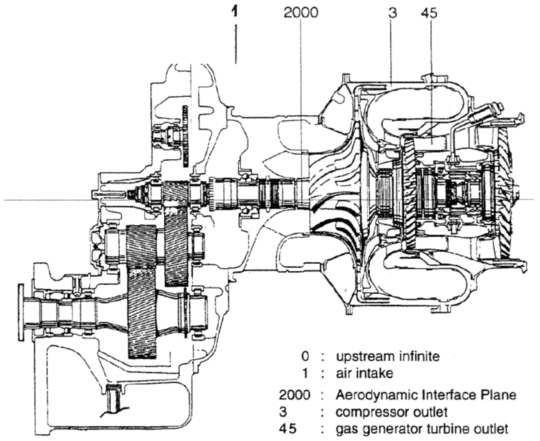

Fig. 1. A turboshaft engine [5].

II. TURBOSHAFT ENGINE DYNAMICS

Consider the following linear turboshaft engine dynamics in parametric form of gas generator speed, $N1$, as [5]:

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

where state $x(t) = dN1$ is gas generator variation, output $y(t) = dT$ is torque variation of engine gear box output shaft, and $u(t) = dC_H$ is fuel flow variation in metering valve. The parameters of the dynamics system are:

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

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

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

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

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

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

TABLE I

SOME PARAMETERS OF A TURBOSHAFT ENGINE MODEL[5]

$N1$ $\%$	$\frac{dCG}{dC_H}$ $\frac{mdaN}{(l/h)}$	$\frac{dC_H}{dN1}$ $\frac{(l/h)}{\%N1}$	$\frac{dT}{dC_H}$ $\frac{mdaN}{(l/h)}$	$\frac{dT}{dN1}$ $\frac{mdaN}{\%N1}$	$\frac{dT}{dN2}$ $\frac{mdaN}{\%N2}$
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

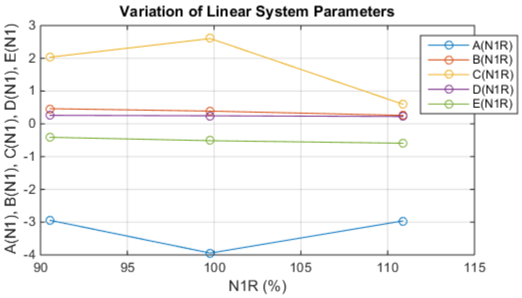

Fig. 2. Parameter variations of a turboshaft engine model

Note that, C_H is fuel flow, $N2$ is power turbine speed, $dN2$ is power turbine speed variation, and NR is rotor speed. Table I gives some parameters of linear dynamic system for various gas generator speed $N1$ (%). Also, $I_G = 0.0138kgm^2$ is gas generator inertia and $NG_{NOM} = 54117t/mn$ is gas generator nominal speed. Parameter variations versus rotor speed $N1R(\%)$ of parameter varying linear dynamic system (1) are illustrated in Fig. 2.

In practice, turboshaft engines are generally used in helicopter systems. The engine is connected to a gearbox and gearbox output is connected to helicopter main rotor with n blades. Rotor speed variation $d\Omega$, engine power tribune $dN2$ and torque variation dT at output shaft has a relation as:

$$d\Omega = dN2 = \frac{1}{\Omega}\int \frac{G_{gb}}{nI_{bld}} dT(t)dt \tag{8}$$

III. HIGH-ORDER SLIDING MODE CONTROLLER DESIGN

Since rotor speed or power turbine speed is measurable, let choose a sliding manifold for dynamic system (1) as:

$$s(t) = dN2 = \alpha \int y(t)dt \tag{9}$$

where $\alpha = {}^{G_{gb}}/_{\Omega n I_{bld}}$ and $y(t) = dT$. Then the time derivative of sliding function can be calculated as:

$$\dot{s}(t) = \alpha y(t) \tag{10}$$

and the second time derivative can be obtained as:

$$\begin{aligned} \ddot{s}(t) &= \alpha \dot{y}(t) \\ &= \alpha C(N1)\dot{x}(t) + \alpha D(N1)\dot{u}(t) + \alpha E(N1)\dot{\nu}(t) \\ &= \varphi(N1, x, u, \dot{\nu}, t) + \gamma(N1)\dot{u}(t) \end{aligned} \tag{11}$$

where

$$\begin{aligned} \varphi(N1, x, u, \dot{\nu}, t) =& \alpha C(N1)A(N1)x(t) \\ &+ \alpha C(N1)B(N1)u(t) \\ &+ \alpha E(N1)\dot{\nu} \end{aligned} \tag{12}$$

and

$$\gamma(N1) = \alpha D(N1) \tag{13}$$

let uncertain function given in (12) be bounded as [1]:

$$\Phi > 0, |\varphi| \leq \Phi$$

and (13) be bounded as:

$$0 < \Gamma_m \leq \gamma \leq \Gamma_M$$

Variation of uncertain functions for dynamic system (1) with parameters defined in Table I are illustrated graphically in Fig. 3 for $|x(t)| \leq x_L$, $|u(t)| \leq u_L$ and $|\dot{\nu}(t)| < \nu_L$. To reduce chattering that occures in conventional sliding mode control technique consider a second order high sliding mode super-twisting algorithm with relative degree 1 as follows [1]:

$$\begin{aligned} u(t) &= -\lambda |s(t)|^{\frac{1}{2}} sign(s(t)) + \vartheta(t) \\ \dot{\vartheta}(t) &= -M sign(s(t)) \end{aligned} \tag{14}$$

where control gains are calculated from the relations as in [1]:

$$M > \frac{\Phi}{\Gamma_m} \tag{15}$$

$$\lambda^2 \geq \frac{4\Phi}{\Gamma_m^2}\frac{\Gamma_M(M+\Phi)}{\Gamma_m(M-\Phi)} \tag{16}$$

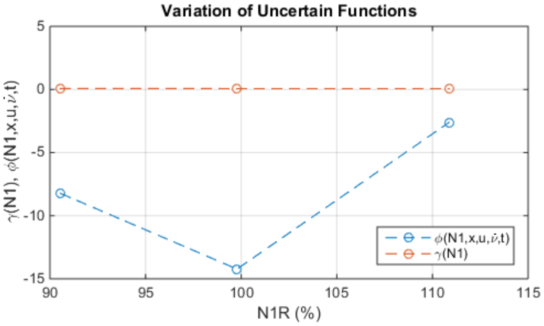

Fig. 3. Variations of uncertain functions

According to the Fig. 3 the bounds of uncertain functions can be calculated as: $\Phi = 15$, $\Gamma_m = 0.6$, and $\Gamma_M = 0.8$. Then control gain can be easily calculated for selected bounds of uncertain functions: $x_L = 10$, $u_L = 20$ and $\nu_L = 1$. So,

$$\frac{\Phi}{\Gamma_m} = 25$$

$$\frac{4\Phi}{\Gamma_m^2}\frac{\Gamma_M(M+\Phi)}{\Gamma_m(M-\Phi)} = 58.1741$$

Finaly, it is suitable to select control gains as $M = 26$ and $\lambda = 8$.

IV. SIMULATION RESULTS

The block diagram of a complete helicopter system with the turboshaft engine connected to gear box and then to the main rotor is given in Fig. 4.

Consider that, main rotor of the helicoper is disturbed by $1000Nm$ step external torque. After running simulation for 12 seconds for N1 @ 100% at sea level the time responses are calculated in Fig. 5 comparatively for considered super-twisting control law and manufacturer's conventional PI based controller. The order of illustrated figures from top to down follows as: rotor torque (Nm), shaft toque at engine gearbox output (mdaN), gas generator speed variation $(\%N1)$, fuel flow (l/h), an sliding function. Note that fuel flow dCH is control input of the turboshaft engine. As seen from simulation results PI based controller has $\%20$ over shoot and long settling time as 7 seconds. On the other, high order sliding mode controller stabilizes the dynamic system less then 2 seconds. Elimination of $1000Nm$ torque error at helicopter rotor increases approximately $6mdaN$ motor shaft torque, increases gas generation speed variation approximately by $1.5\%N1$, with extra $13l/h$ fuel flow with super-stwisting algorithm.

Now assume that, main rotor of the helicopter is disturbed by a gust decribed with a sinusoidal function as $g(t) = 300sin(0.5t)Nm$. Time responses for N1 @ 100% at sea level are illustrated comparatively in Fig. 6 for 12 seconds of time interval. As seen from simulation resuls, manufacturer's conventional PI controller can not stabilize the system. The rotor torque devation oscillate with $200Nm$ amplitude under a sinusoidal gust that defects flaying and handling qualities of the rotorcraft (see rotor torque plot, dRotor in Fig. 6). On the other hand, high order sliding mode controller stabilizes the dynamic system again less then 2 seconds and forces rotor torque devation to keep zero value with light changes in generator speed f $0.8\%N1$ and fuel flow rate dCH of $8l/h$.

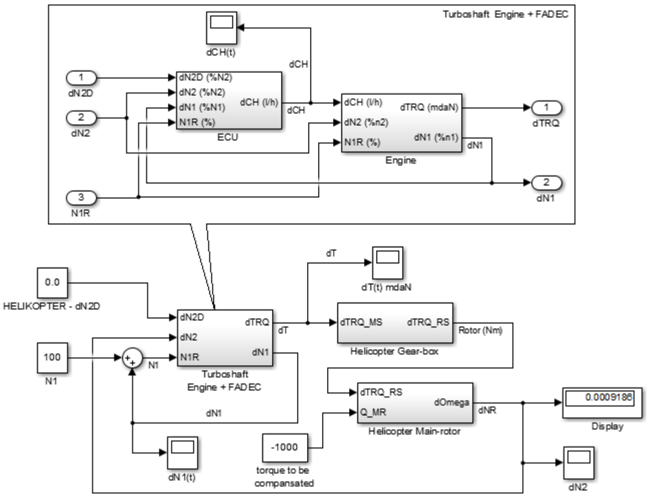

Fig. 4. Matlab-Simulink block diagram turboshaft engine - helicopter system

Disturbance attenuation performances at the rotor disk of super twisting based control system is successful and satisfactory for helicopter handling qualities and agile maneuvering as described in an aeronautical design standard [7].

V. 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. A high-order sliding mode control system architecture is proposed for faster stabilization to satisfy helicopter handling qualities and agile maneuvering performances under parametric changes of turboshaft dynamics. Successful simulation results show effectiveness and performance improvement of proposed control algorithm.

REFERENCES

[1] L. Fridman, A. Levant, *Higher Order Sliding Modes, Chapter 3*, Marcel Dekker Inc, CRC Press, 2002.

[2] V. Utkin, *Discussion Aspects of High Order Sliding Mode Control*, IEEE Transaction on Automatic Control, doi: 10.1109/TAC.2015.2450571, 2015.

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

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

[5] E. Abdulhamitbilal, *ITU-Light Commercial Helicopter Flight Dynamics, Stability Analysis, and Interconnected Control Systems Design*, PhD Thesis, Advisor: Prof.Dr. E.M. Jafarov, ITU-Library, Istanbul, 2010.

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

[7] Aeronautical Design Standard, *Handling qualities requirements for military rotorcraft* U.S. Army Aviation and Missile Command, Aviation Engineering Directorate, Rept. ADS-33E-PRF, Redstone Arsenal, AL, 2010.

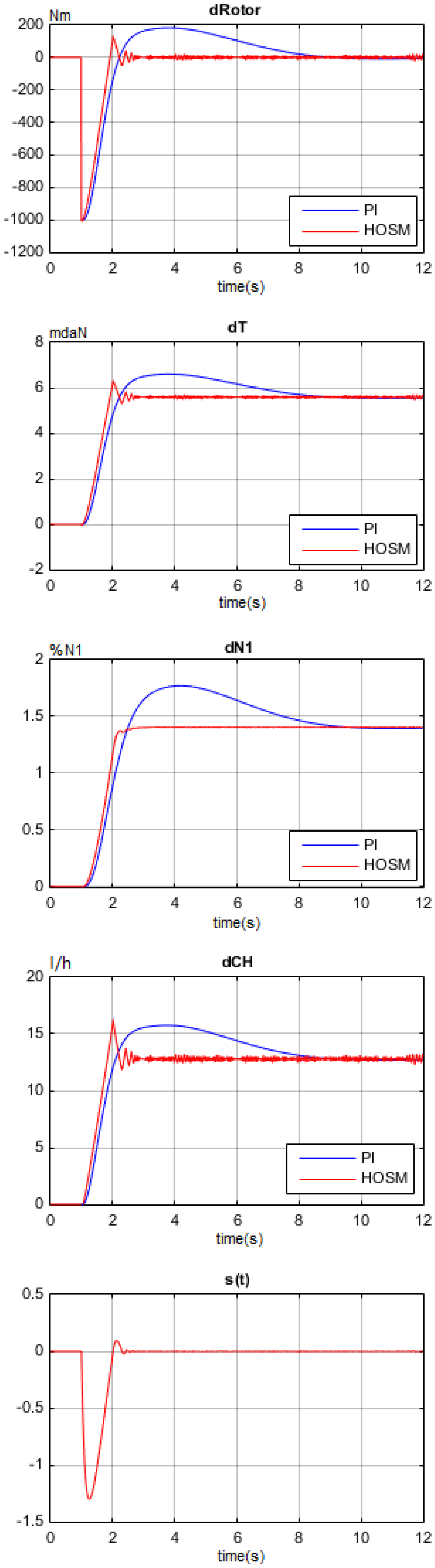

Fig. 5. Time responses of turboshaft engine dynamics under 1000 Nm step input disurbance

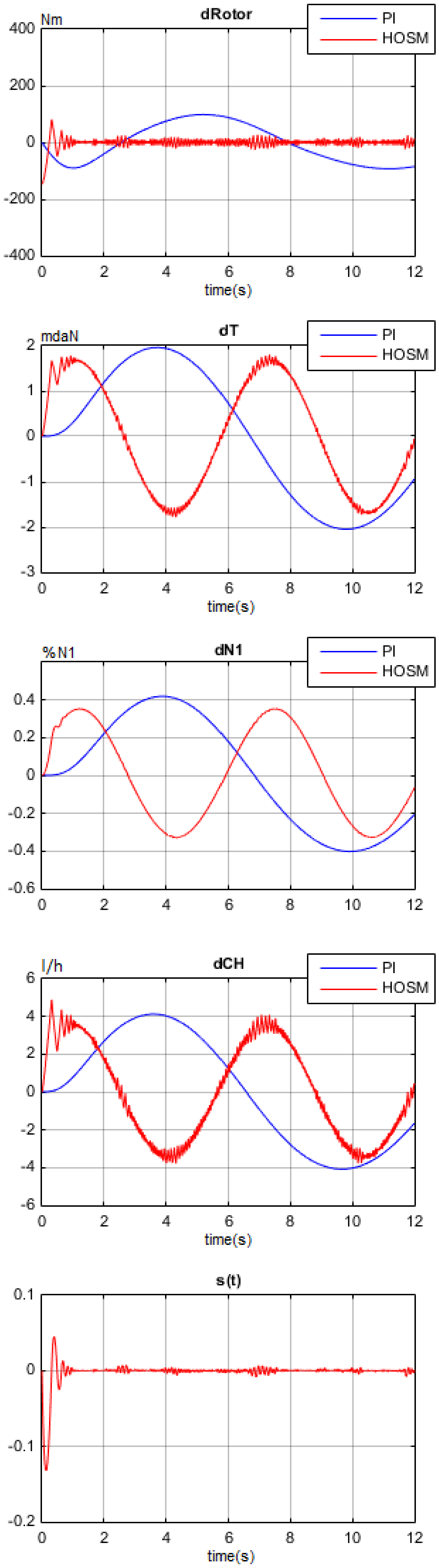

Fig. 6. Time responses of turboshaft engine dynamics under sinusoidal disturbance