Comparative Study of Lyapunov Based Control Methods for Electro-Hydraulic Fuel Servo Application

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doi: https://doi.org/10.37285/bsp.SACAD2025.28

***Abstract*— The Electro-hydraulic Actuation Systems (EHAS) are widely employed for precise fuel control in gas turbine engine applications, where robust and accurate actuation is essential for reliable engine operation. However, the inherent nonlinearities and parameter uncertainties of such systems pose challenges in control using traditional Proportional-Integral-Derivative (PID) control method. This paper presents a comparative study of Lyapunov-based control methods- Backstepping control (BSC), Sliding mode control (SMC), Super Twisting Control (STC) and comparison against a baseline PI controller for fuel control using EHAS for a developmental gas turbine engine. While the PID controller remains popular for easy implementation, it often renders desired system performance in a narrow operating range only. The presence of nonlinearities, unmodelled dynamics and external disturbances makes it even more challenging for PID controller to deliver the intended performance. Sliding mode control, on the other hand, offers highly accurate tracking and effectively counters non-linear effects. However, this robustness comes at the cost of higher control effort and the well-known chattering phenomenon. The Backstepping controller achieves desired performance even in the presence of uncertainties and provides smother control with lower control effort compared to SMC & STC. Nonetheless, its performance may be slightly inferior to SMC & STC in terms of tracking accuracy and steady state error may occur if the servo valve's null current is not accurately known or adaptively estimated. The detailed simulation studies are carried out with the designed controllers for closed loop system performance evaluation. Further experimental validation of each control method is carried out on actual fuel control system. Overall, this work presents a detailed comparison of mentioned control methods, highlighting their strengths and limitations without drawing a definite conclusion about which method is universally best. The control performance matrix for all methods is also presented.**

Keywords— Lyapunov-based Methods, Sliding mode control, Backstepping control, Electro-hydraulic Actuation Systems (EHAS)

I. INTRODUCTION

Electro-hydraulic Actuation systems (EHAS) are widely used in aerospace, automotive and industrial applications due to their high-power density, fast dynamic response and precise control capability. In gas turbine engines, EHAS play a crucial role in regulating fuel flow to meet thrust demands while maintaining desired transient performance [1]. However, the non-linear characteristics of Electro-hydraulic actuation systems including flow-pressure dynamics, dead bands, and parameter uncertainties pose significant challenges for control design [2] and [3].

Traditionally, Proportional-Integral-Derivative (PID) controllers have been the standard control methods for fuel servo control applications due to their simplicity and ease of implementation [4]. Despite their advantages, classical linear controllers often require extensive gain tuning and are not very effective in maintaining robust performance under changing operating conditions and non-linear effects [5]. To achieve desired performance in wide operating range, gain scheduled PID control method is used provided the accurate linear models at different operating conditions are available. To overcome these limitations of PID controllers, several advanced nonlinear control methods have been actively explored and demonstrated in literature.

Backstepping control, developed by Kokotovic [6], provides nonlinear design framework that stabilizes feedback non-linear systems through a recursive design process. In recent studies, Backstepping has proven effective for electro-hydraulic actuator control [7] [8], showing smother control and improved tracking and transient response than conventional PID controllers for varying operating conditions. A discontinuous projection based adaptive robust controller (ARC) is developed in [1] to provide prescribed tracking and transient performance in the presence of parameter variations due to inertial loads and non-linearities such as frictional forces and disturbances. Adaptive Backstepping approach has further improved robustness by compensating for uncertain parameters in real time [8].

A sixth order model is developed in [10] and SMC is implemented in simulation taking the sliding surface as a function of drive current and position. Theoretical analysis and numerical simulation for a third order model is shown in [14]. SMC is compared with P, PD and PID controllers with metrics such as mean square error and controller effort. This model considers load variation, friction and leakage as uncertainties. Reference [15] uses varying boundary layer to minimize chattering in control signal. Large boundary layer width is preferred to reduce chattering, whereas smaller width boundary layer results in better tracking performance. Adaptive SMC scheme is exhibited in [16] to compensate for nonlinear uncertainties. A dynamic SMC uses derivative of sliding variable to smoothen the control variable in [17]. A novel method of PID Sliding Mode is presented in simulation in [18], wherein the traditional Sliding variable replaces the error term in traditional PID control. The result is a comparatively continuous switching function and consequently the control effort. Reference [19] has proposed multiple surface Sliding Control law for unstable Servo valves. An intentionally made unstable single stage valve is used and stabilized via high bandwidth control, which ensures significantly faster response performance. In a similar way [20] proposes use of sliding mode to use on-off solenoid valve for proportional actuation.

Higher order Sliding modes for control of mechanical systems are also available in literature. References [21] and [22] describes second order Sliding mode control for applications such as overhead cranes, mechanical systems with coulomb friction, railway active pantograph, Power electronics drives and force-position robotic manipulators. Super Twisting Algorithm which is a higher order sliding mode for control of electro-hydraulic actuation system through a solenoid is used in [23].

This paper compares the performance of baseline PI controller, Backstepping controller, Sliding mode control and Super-Twisting Controller for fuel control in an EHAS. The aim is to highlight the relative benefits and limitations of each control method in terms of tracking precision, transient performance, steady state performance, control effort and practical implementation constraints.

II. Plant Model

The plant under consideration is a Fuel Control System (FCS) for aero-gas turbine engine. The FCS consists of a power pack and Fuel Metering Unit. The LP and HP pumps are used to provide pressurized fuel to overcome the burner pressure. Pressure regulator valve is used to maintain constant pressure difference across metering valve. An Electro-Hydraulic Servo Valve (EHSV) is used for actuation of the Metering valve and a LVDT is used as position feedback for closed loop position control. The fuel is metered into engine by a closed loop valve position control for modulation of metering orifice, across which the pressure is maintained constant. A schematic of a typical FCS is as shown in Fig. 1.

For control of valve position in closed loop, only the position dynamics are considered. A second order transfer function-based model is derived experimentally under various operating conditions simulated in rig conditions and is validated against a theoretical reduced model. An average model of the transfer function is used for derivation of Lyapunov based control methods discussed in this paper.

$$\frac{x(s)}{i(s)} = \frac{1.0}{0.02s^2 + s} \tag{1}$$

Where, x denotes the valve position and i denotes the drive current input. The considered plant is kept intentionally simple and does not consider higher order dynamics. The parameters simulated in fuel system rig are prime mover speed to emulate engine spool driven gearbox input and fuel system downstream pressure emulating burner pressure for different operating conditions. Transfer functions for the plant at various operating conditions for ground static conditions are obtained experimentally, as shown in Table I.

TABLE I. TRANSFER FUNCTIONS AT VARIOUS OPERATING CONDITIONS

Operating conditions			Transfer Function model
Engine speed (%)	Pump RPM	Burner pressure (KPa)	
74	4250	300	$\frac{\mathbf{0.76}}{\mathbf{0.023s^2+s}}$
85	4900	800	$\frac{0.91}{0.022s^2+s}$
90	5150	1035	$\frac{1.05}{0.02s^2+s}$
98	5600	1780	$\frac{1.2}{0.018s^2+s}$

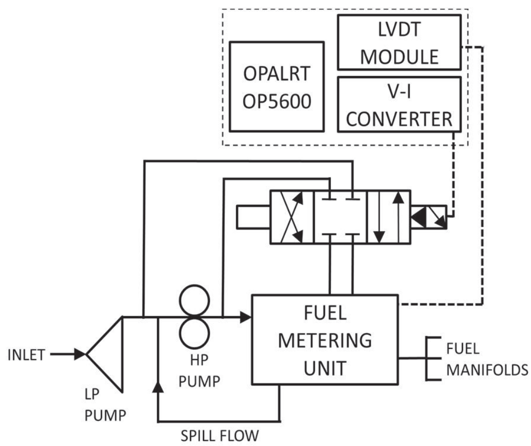

Figure 1: Fuel Control System schematic and experimental setup

III. Lyapunov Method 1: Backstepping Control

The Backstepping control method is a well- established and commonly used method for stabilizing nonlinear systems that can be organized in a strict-feedback structure. This approach developed by Kokotovic is now widely regarded as a standard method in non-linear control applications [6].

Backstepping method relies on the principle of Lyapunov stability, which provides a practical way to check whether the control law will keep the system stable under all operating conditions. Lyapunov function is mathematical measure of system's energy or deviation from desired state. To guarantee stability, the chosen Lyapunov function must satisfy two conditions:

1. The function must always be positive definite.

$$V(x) > 0 \; for \; all \; x \neq 0, \qquad V(0) = 0$$

2. Time derivative must be negative definite or negative semi definite.

$$\dot{V}(x) \leq 0$$

In Backstepping method, the Lyapunov function is constructed step by step for each state subsystem. When multiple states are involved, the Backstepping method adds new terms to the Lyapunov function for each error signal and chooses the virtual controls and final input so that the conditions of Lyapunov stability are satisfied at each step. The Backstepping control law for EHAS based fuel control is derived in the following section.

The EHAS transfer function can be written in second order differential equation form as:

$$0.02\frac{d^2x}{dt^2} + \frac{dx}{dt} = u \qquad (2)$$

Where, x denotes valve position and u denotes the EHSV drive current input.

State space representation of system (2) is as shown below:

$$\dot{x_1} = x_2 \qquad (3)$$
$$\dot{x_2} = -50x_2 + 50u \qquad (4)$$
$$\text{where } x_1 - \text{valve position} \;\; x_2 - \text{actuator velocity}$$

The states of the Backstepping controller can be defined as:

$$z_1 = x_1 - x_d \quad (Trackingerror) \qquad (5)$$
$$\text{where } x_d \text{ is demanded valve position}$$
$$z_2 = x_2 \qquad (6)$$

State space representation of Backstepping controller states:

$$\dot{z_1} = \dot{x_1} - \dot{x_d} = z_2 \qquad (7)$$
$$\dot{z_2} = -50z_2 + 50u \qquad (8)$$

Considering the candidate Lyapunov function:

$$V_1 = \frac{1}{2}{z_1}^2 \qquad (9)$$
$$\dot{V_1} = z_1 * \dot{z_1} = (x_1 - x_d) * z_2 \qquad (10)$$

z_2 can be considered as a virtual control signal and chosen such that Lyapunov function becomes stable in (9).

$$z_{2\alpha} = -k_1(x_1 - x_d) \; where \; k_1 > 0 \qquad (11)$$
$$\dot{z_{2\alpha}} = -k_1 * \dot{x_1} \qquad (12)$$

New error variable is found from actual actuator velocity and virtual control signal.

$$e_2 = z_2 - z_{2\alpha} \qquad (13)$$

Now, considering the new candidate Lyapunov function taking the previous function into account.

$$V_2 = V_1 + \frac{1}{2}{e_2}^2 \qquad (14)$$
$$\dot{V_2} = z_1 * \dot{z_1} + e_2 * \dot{e_2} = -k_1 * (x_1 - x_d)^2 \, (z_2 - z_{2\alpha}) * (\dot{z_2} - \dot{z_{2\alpha}}) \qquad (15)$$

Put values from (8) and (12) in(15):

$$\dot{V_2} = -k_1 * (x_1 - x_d)^2 + (z_2 - z_{2\alpha}) * \left((-50z_2 + 50u) + k_1 * \dot{x_1}\right) \qquad (16)$$

Control signal u must be derived to make Lyapunov function V_2 stable.

The Backstepping control law (u) is derived as below and its implementation is shown in Fig. 2. The washout filter/differentiator is converted to discrete domain using c2d MATLAB command.

$$u = \frac{1}{50}\left(k_1 * k_2(x_d - x_1) + x_2(50 - k_1 - k_2)\right) \qquad (17)$$

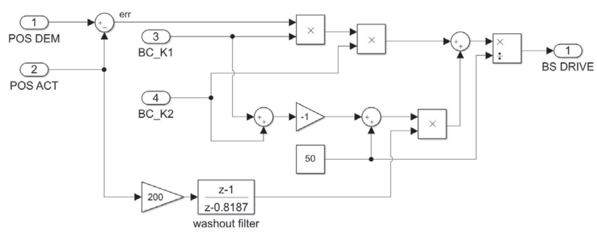

Figure 2: Simulink implementation of Backstepping Controller

IV. Lyapunov Method 2: Sliding Mode Control

For reference tracking, the states for Sliding variable definition are modified to error in output state i.e.

$e = y_c - y$ Thus, σ is defined as,

$$\sigma = ce + \dot{e}, c > 0 \qquad (18)$$

σ dynamics are given by,

$$\dot{\sigma} = c\dot{e} + \ddot{e} = c(\dot{y_c} - \dot{y}) + \ddot{y}_c - \ddot{y} = \ddot{y}_c + c\dot{y_c} - f(y, \dot{y}, t) - c\dot{y} - u \qquad (19)$$

Define $\ddot{y}_c + c\dot{y_c} - f(y, \dot{y}, t) - c\dot{y} = \varphi(y, \dot{y}, t)$

This Unknown disturbance is assumed to be bounded i.e. $|\varphi(y, \dot{y}, t)| \leq M$. Thus:

$$\dot{\sigma} = \varphi(y, \dot{y}, t) - u \quad (20)$$

Therefore,

$$\sigma\dot{\sigma} \leq \sigma(\varphi(y, \dot{y}, t) - u) \leq |\sigma|M - \sigma u \quad (21)$$

Selecting $u = \rho sign(\sigma)$ for conventional SMC design,

$$\sigma\dot{\sigma} \leq |\sigma|M - \rho sign(\sigma)\sigma\dot{\sigma} \leq |\sigma|M - |\sigma|\rho\sigma\dot{\sigma} \leq |\sigma|(M - \rho) \quad (22)$$

Now, by Sliding Mode reachability condition,

$$\sigma\dot{\sigma} \leq -\frac{\alpha}{\sqrt{2}} \vee \sigma \vee \quad (23)$$

Therefore,

$$|\sigma|(M - \rho) = \frac{-\alpha}{\sqrt{2}} \vee \sigma \vee \quad (24)$$

Thus,

$$\rho = M + \frac{\alpha}{\sqrt{2}} \quad (25)$$

The SMC law becomes $u = \rho sign(\sigma)$, where the control gain ρ depends on the assumed bound of disturbances and the required convergence time.

Further, certain modifications are necessary for implementation purposes. The sliding variable defined for reference tracking contains derivative of error term. For implementation of the current SMC law, the derivative is simply numerically computed using previous iteration data and smoothened by a low pass filter.

For minimization of chattering, a known downside of using SMC, the signum function is replaced with a sigmoid function. Thus $sign(\sigma)$ becomes,

$$sign(\sigma) \approx \frac{\sigma}{|\sigma| + \epsilon} \quad (26)$$

Where, ϵ is a small positive scalar. The selection of ϵ is a tradeoff between ideal sliding mode performance and smoothness of control effort parameter. Fig. 3 shows implementation of the conventional SMC.

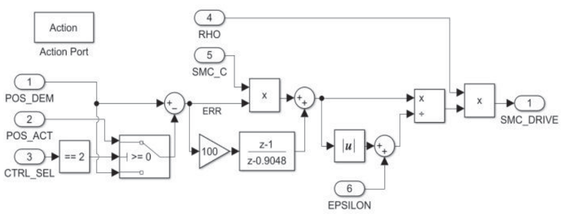

Figure 3: Simulink implementation of Sliding Mode Controller

V. Lyapunov Method 3: Super Twisting Control

Conventional Sliding mode controllers exhibit high frequency control effort, which can be detrimental for mechanical systems. The Super-Twisting controller (STC) is a continuous controller which still ensures properties of first order sliding mode.

For system (3), STC is given by,

$$u = -\lambda|\sigma|^{\frac{1}{2}} sign(\sigma) + w \quad (27)$$
$$\dot{w} = -\alpha sign(\sigma)$$

$$\text{If } \lambda > 1.5\sqrt{M} \text{and } \alpha > 1.1M \quad (28)$$

Equation (27) ensures finite time convergence [levant2005]. STC does not require measurement of $\dot{\sigma}$ and thus is suitable for practical implementation. In practice, the controller parameters are never assigned according to the inequalities (28), as the real system is rarely known exactly and model is almost always inadequate. Thus the controller parameters are mostly tuned through a simulation program [9].

Fig. 4 shows implementation of STC for experimental comparison.

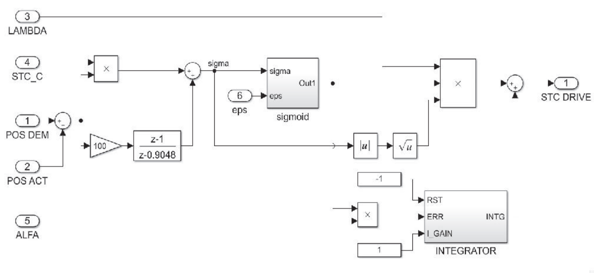

Figure 4: Simulink implementation of Super-Twisting Controller

VI. Software in Loop Simulation Results

The plant model with different controller configurations has been modeled in Simulink to perform closed-loop valve position control simulation. The impact of nonlinearities such as dead band, quantization and measurement noise has been investigated within the closed-loop framework. The model includes sinusoidal disturbance acting on position feedback. The effects of digital controller and signal conditioning elements are emulated by adding quantization noise and white noise in the position feedback. Dead band is incorporated to represent servo valve null effect. A differentiator combined with an appropriately tuned low pass filter is used to get position or error derivative. The closed loop performance for the above described control methods is compared with the baseline PI controller for step and sinusoidal valve position demands. Simulation results demonstrate that the SMC, STC and Backstepping control deliver better performance than the baseline PI controller. SMC achieves the highest tracking accuracy but at the cost of higher control effort, STC exhibits comparable time response, with intermediate disturbance rejection at slightly reduced control efforts while the Backstepping controller delivers slightly less disturbance rejection with further reduced control effort, as shown in Fig. 5 and Fig. 6. Control performance matrix for all the methods is shown in Table II.

These simulation results support the feasibility of evaluating the designed controllers on actual fuel system hardware.

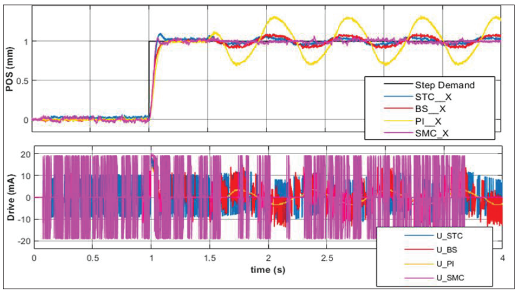

Figure 5: Step demand comparison of BSC and SMC against PI controller

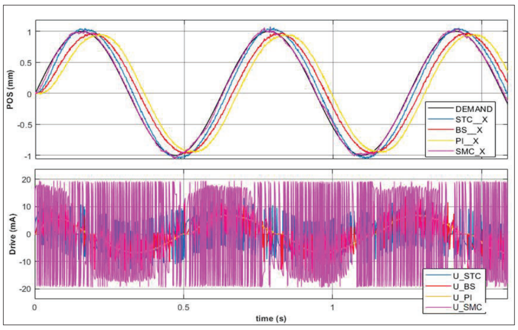

Figure 6: Sinusoidal demand response comparison of BSC and SMC against PI controller

TABLE II: CONTROL PERFORMANCE MATRIX FOR ALL METHODS

Control Method	Rise time (sec) (Step response)	Disturbance (mm) (pk-pk)	Phase Delay (degree) (Frequency Response)
STC	0.06	0.15	8.79
BSC	0.08	0.16	11.3
SMC	0.055	0.1	4.3
PI	0.094	0.6	19.5

VII. EXPERIMENTAL RESULTS

The control methods described above- Backstepping, Sliding Mode Control, Super-Twisting Control and PI control have been experimentally verified in the fuel system rig which consists of prime mover for fuel pumps emulating the engine spool drives. A rapid prototyping OPAL-RT® based system serves as the real time controller platform, executing the control algorithms in 1ms step size to ensure high fidelity closed loop performance. The OPAL-RT system is interfaced with Voltage to Current (V2I) converter module and LVDT signal conditioning modules as shown in Fig. 1. The experimental setup enables testing of designed controllers under realistic operating conditions with intended accuracy. Specifications of the test setup are indicated in Table II. Findings of the experiment with the results are explained in the section below.

TABLE III. DETAILS OF EXPERIMENTAL SETUP

Module	Specifications
OPALRT OP5600 Analog Out Analog In	Intel Xeon E5, Redhat Linux, 16 bit, +/- 15V, 15mA 16 bit, +/-20V,820kHz BW
V-I module, VC2124	+/- 10V input, +/-20mA output, 2.5kHz BW
LVDT conditioner, Canopus LVDT-DBV	5 wire LVDT conditioner. 5.3Vrms, 2kHz excitation. +/-10 V Output.

The loop performance targets are as per engine stability and operation requirements. The Backstepping control gains parameters used are k1 = 35, k2 = 28. The SMC tuning parameters used are $c = 100$, $\rho = 15$ and$\epsilon = 3$. The derivative of error is computed using a washout filter. The STC parameters used are $c = 200$, $\lambda = 1.5$ and $\alpha = 15$. The parameters for all of the controllers compared are tuned first in a simulation program. A provision to switch controllers is implemented to cater for operational safety during rig operations.

Fig. 7 shows a baseline PI control performance. The tuned PI parameters are kp = 15 and ki = 1. The PI control position response shows a low frequency oscillation, probably because of dead-band manifested due to EHSV second stage spool overlap or due to hydraulic fuel contamination.

Fig. 8 shows comparison of the described Lyapunov based methods viz., Backstepping, Conventional Sliding mode and Super-Twisting Controllers. As can be seen, SMC shows best robustness against disturbance attributed to dead-band effect at the expense of high magnitude, high frequency control effort. STC exhibits better time response, with intermediate disturbance rejection at slightly reduced control efforts. Backstepping controller shows least control efforts among the compared methods and offers intermediate disturbance

rejection. Control performance matrix for all methods is shown in Table IV.

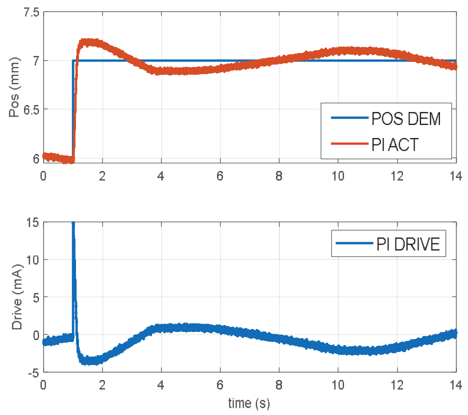

Figure 7: Response of PI controller

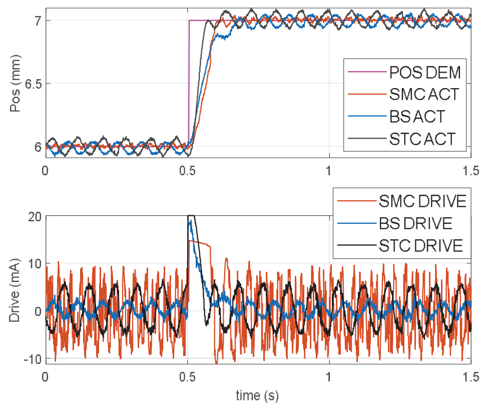

Figure 8: Experimental comparison of Backstepping, Sliding Mode & Super-Twisting Controllers

TABLE IV: CONTROL PERFORMANCE MATRIX FOR ALL METHODS

Control Method	Rise time (sec) (Step response)	Disturbance (mm) (pk-pk)
STC	0.054	0.14
BSC	0.072	0.11
SMC	0.079	0.05
PI	0.086	0.35

Parametric simulation studies were done for tuning of the controllers. It was seen that when BS gain k2 approaches lower values, the performance of BS tends towards that of PI control. Moreover, experiments with different servo valves revealed that EHSV null current information is required for BS implementation, especially if the null current variation is large over the operation. Approximate null value can be used to offset BS control input, but large variations cannot be addressed due to lack of inherent integral element in BS control. Reference [7] indicates the adaptive estimation of null value adjustment for such issues. No null current information is required for SMC & STC controllers due to their inherent switching structure.

For further aggressive tuning of these controllers to better reject disturbances needs information of critical frequency modes of the servo elements. Filtering of control input in these frequency bands can be implemented to avoid exciting those modes during operation.

VIII. CONCLUSION

Advanced Lyapunov based control methods of Backstepping control, Conventional Sliding Mode and Super-Twisting Control are derived and the experimental performance and required control effort is compared for an Electro hydraulic Actuation System (EHAS) of an aero- gas turbine engine fuel control system. Efficacy of the control methods derived with simple model is shown for unmodelled dynamics and parameter uncertainties. The response comparison with baseline PI control is also shown indicating improvement in handling uncertainties while meeting the transient and steady state control performance.

ACKNOWLEDGMENT

The Authors thank Director, Gas Turbine Research Establishment (GTRE, DRDO) for permission to publish this paper.

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