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Simultaneous feedforward online command rate limiter filters for existing controllers

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Abstract: One of the biggest challenges in controller design for a mechatronics system is the actuator limitations. Either response time of the actuator or the input constraints creates limits for the controller performance and stability. In this study a novel feedforward online rate limiter scheme for arbitrary input signals is introduced by taking velocity, acceleration and jerk constraints into account, and it is investigated that how the control effort and system response is affected by the demand signal's rate of change limitations. A fin actuation system for a guided missile is given as an example where the demand signal comes from the guidance system online. Different online rate limiting schemes are reviewed, and simulations are carried out for comparison. Proposed method is shown to be effective via simulation and confirmed by experimental results for the existing controller.

Key words: Rate limiting filter, velocity limiter, acceleration limiter, jerk limiter, control saturation, missile fin actuation system

1. Introduction

A guided missile system needs to be stabilised after released from the aircraft's wing or internal bay and is directed to the target in concern. This is mostly done by using aerodynamic surfaces, which are called fins. These fins are exerted by fin actuation systems or in short FAS (fin actuation system). FAS creates an angular motion on the fins depending on the commands created by the missiles guidance system. By that way, the munition manages to stabilise and keep up with the right path way that is determined by the relevant guidance algorithm of the system [1].

Guidance computer creates the fin commands just in time and expects the FAS to follow the angular deflection commands for the fins as close as possible. As the fin actuation systems are mechatronics devices, there are some physical limitations. These physical limitations create nonlinearities in the system, which might be listed below: [2]:

- Speed Limit: That is limited by either the supply voltage or mechanical integrity requirement.
- Power Limit: Electrically, for a constant voltage, power is limited by the supply current.
- Mechanism Dynamics: Viscous friction, mass moment of inertia, etc. effects how quickly the system can respond.

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Often, since the reference commands are not properly filtered, the above-mentioned nonlinearities occur, and, in this case, current and voltage limits are violated. If the required power is not supplied to the FAS, feedback control system behaves as an open loop system, which makes the system vulnerable to external disturbances and parameter uncertainties. If system stability is lost, there may come into catastrophic effects, which is not required in any system. In the literature, there are many types of solutions studied to cope with the actuator saturation in control applications.

Tan et.al. in their study [3] proposed an iteratively adjusted reference signal for high precision control applications. They used radial basis function (RBF) network and an iterative learning controller for the reference adjustment. The main aim of this study is to improve the tracking performance under nonlinear effects for high precision applications. Although preliminary results show that the method is effective for reducing the tracking error, the proposed method requires some iteration, which makes it difficult for the high-speed real time application.

Model predictive control (MPC) technique is another method suggested for actuator amplitude and rate saturation in [4, 5]. Giovanini[5] in their study formulate the problem as an equivalent optimal control and introducing AWBT (anti-windup-bumpless-transfer) method to be used together with the MPC. This method provides some improvements over unconstrained reference response and runs faster compared to the controllers that require on-line optimisation. However, closed loop stability and sensitivity analysis are not carried out; hence, the stability may not be guaranteed with actuator constraints. MPC is a well-established method for the constrained actuator problems, while anti-windup techniques have stronger background and are widely used in practical applications because of its ease of use [6]. De dona et.al. [7] established some connections between anti-windup techniques and MPC and showed by simulations that the performance of anti-windup strategy is similar to that of MPC. Anti-windup compensator for sliding mode control (SMC) through a linear matrix inequalities (LMI)-based synthesis is suggested in [8]. They validated their design of SMC with anti-windup scheme via simulations and showed that the method is effective in decreasing performance deterioration and maintain stability in the case of input saturation.

Although the controller design with MPC and anti-windup strategies produce satisfactory results in the case of actuator limitations, they require changing the design of the existing controller. Moreover, MPC requires the future knowledge of the set point in order to accomplish path optimisation to avoid actuator saturation. In order to treat this problem, reference governor techniques are widely used in the literature [9–13]. Reference governors are supplementary techniques for controllers, which yields to enforce input and output constraints by adjusting the reference signal when necessary. Garone et.al. [14] provides an extensive survey in their study presenting different reference governor design strategies for linear and non-linear plants and show their implementations. Similar to MPC and anti-windup techniques they require the feedback of the system output as well. Although it is a theoretically well-established method, its implementation is still needs to be developed because of its complexity.

Solution to requirement of feedback problem can be employed by introducing a filter in the feedforward path. Chen et.al. [15] proposed a trajectory generator for an optimal path in point-to-point control by considering jerk constraints. Their method requires the set point value for the gain calculations and the time optimal trajectory generation that makes it impossible for arbitrary input signals. Nakabayashi et.al. [16] suggested a filter based on model error compensation technique for arbitrary input signals with velocity and acceleration constraints. Their method shows satisfactory results; however, the velocity and acceleration adjustment parameters solely depend on the shape of input signal. On the other hand, they do not have jerk constraint and simultaneous constraints in their study.

In this study, we propose a filter in the feedforward path having the capability of filtering velocity, acceleration and jerk constraints simultaneously requiring no parameter adjustment for most of the signal types. Computationally efficient method is designed in discrete time making it successful for real-time applications. By comparing the simulation results with [16], it has been shown that the proposed method is superior to the previous study for filtering the input signal with rate constraints. Additionally, our method is shown to be effective in reducing the control effort and increasing the tracking performance of an existing controller designed for a fin actuation system (FAS) via real-time application. Conclusions are drawn that using the proposed filter one can reduce both the price of the subcomponents used in the system by smoothing the trajectory and the power requirement.

2. Design strategy of the reference rate limiting filter

To make it easier for real time implementation, the design of the filter is studied in discrete time. This filter is placed just before the pre-designed control algorithm as shown in Figure 1 so that it can be used in any control application.

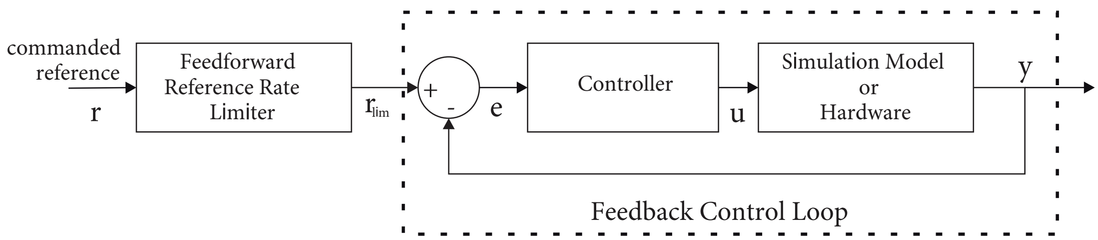


Figure 1. Feedforward limiter and feedback control loop.

The commanded reference can be in any shape continuous or discontinuous where the suggested filter design can filter the input with regard to its first, second and third derivatives, which may also be called as velocity, acceleration and jerk constraints. In this section, filter design for only velocity constraint, acceleration and velocity constraint together, and finally three constraints such that jerk+acceleration+velocity jointly are proposed.

2.1. Velocity limiter

This filter only takes the first derivative into account and for a step command reference a ramp signal is created. This is achieved by taking the first derivative of the signal by using the limited output as feedback as shown in Figure 2.

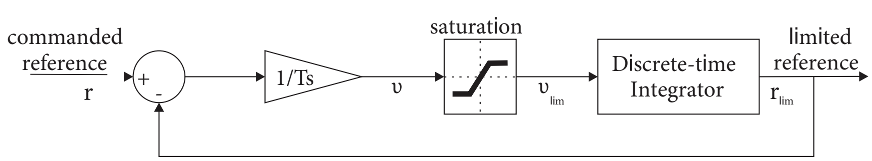


Figure 2. Velocity limiter block diagram.

Velocity is calculated as in Equation (1) such that two point discrete differentiation using the previous value from the limited reference.

$$\nu_{lim}^{[i]} = sat\left(\frac{r^{[i]} - r_{lim}^{[i-1]}}{t^{[i]} - t^{[i-1]}}\right)\Bigg|_{-\nu_{max}}^{\nu_{max}}, \qquad i \in \mathbb{N}, \qquad r_{lim}^{[0]} = 0. \tag{1}$$

Here, i denotes the current value of the variables, which may go up to infinity. Sampling period $T_s = t^{[i]} - t^{[i-1]}$ is assumed to be constant for each time step which is the case for most of the real time applications in digital control systems. $t^{[i]}$ and $t^{[i-1]}$ are current and previous time values, $r^{[i]}$ and $r_{lim}^{[i]}$, respectively, the unfiltered commanded reference's current value and filtered reference signals previous value. First order differentiation gives the velocity, which is limited for $\pm\nu_{max}$ with the nonlinear operator $sat(.)$, which is a static saturation function defined in Equation (2).

$$\xi_{lim} = sat(\xi) = \begin{cases} -\xi_{max} & \text{if} \quad \xi \leq -\xi_{max}, \\ \xi & \text{if} \quad -\xi_{max} < \xi < \xi_{max}, \\ \xi_{max} & \text{if} \quad \xi \geq \xi_{max}. \end{cases} \tag{2}$$

In general, symmetric upper and lower bounds are used; however, for generality Equation (1) can be rewritten to be applied for asymmetric limits. The next step is to take the discrete integral of the saturated velocity to in order to estimate the velocity limited reference signal. Using forward integration the following equation gives the limited reference signal.

$$r_{lim} = r_{lim}^{[0]} + \lim_{n\to\infty} \sum_{i=1}^{n} \underbrace{\left(t^{[i]} - t^{[i-1]}\right) \nu_{lim}^{[i]}}_{r_{lim}^{[i]}}, \qquad \text{where } r_{lim}^{[0]} = 0. \tag{3}$$

Similar definition can be made for $\nu_{lim}^{[i]}$ that it is the limited velocity value of $\nu^{[i]}$ at current time step after saturation.

2.2. Velocity + acceleration limiter

In this type, both the first and second derivative limitations will be taken into account so that the velocity profile of trapezoid shape is obtained in the case of a step reference command. There are three design steps:

- Velocity limitation loop : The exactly same loop is used as given in Section 2.1
- Acceleration limitation loop : The input of this loop is the limited velocity of the first loop. Similar derivative, saturation and integration steps are taken for the velocity input to obtain position data with a limited acceleration.
- Correction action : As the acceleration is limited as well as the velocity output, position may not converge to the demanded value; therefore, a compensation term is required.

Velocity+acceleration limitation filter block diagram is depicted in Figure 3.

The loop equation for the acceleration limitation is written as in Equation (4).

$$a_{lim}^{[i]} = sat\left(\frac{\nu_{lim-1}^{[i]} - \nu_{lim-2}^{[i-1]} + \left(r^{[i]} - r_{lim}^{[i-1]}\right)\Gamma}{t^{[i]} - t^{[i-1]}}\right)\Bigg|_{-a_{max}}^{a_{max}}. \tag{4}$$

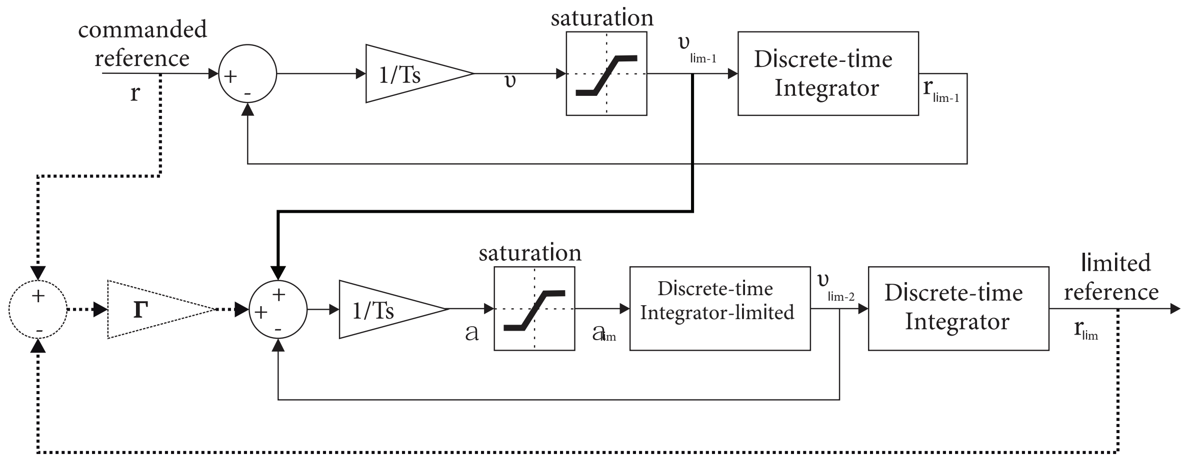


Figure 3. Acceleration limiter block diagram.

The saturation operation as in Equation (2), is used for acceleration limitation for $\pm a_{max}$. The constant $\Gamma = \frac{a_{max}}{\nu_{max}}$ provides a correction on the acceleration. Substituting Γ in Equation (4) and making some mathematical manipulations the following equation is obtained.

$$a_{lim}^{[i]} = sat\left(a_{\nu}^{[i]} + a_{max}\Upsilon^{[i]}\right), \qquad \Upsilon^{[i]} = \frac{\nu^{[i]}}{\nu_{max}}. \tag{5}$$

Here, $\Upsilon \in \mathbb{R}$ is a unitless variable that is a scaling factor for the maximum acceleration limit. By this way, it is ensured that the position is reached to the demanded value even if $\nu_{lim-1}^{[i]}$ goes to zero or changes direction before $r_{lim}^{[i]}$ catches the commanded reference $r^{[i]}$.

The filter uses two consequent discrete integrals where the first integrator is bounded for velocity limitation, in order to obtain the acceleration and velocity limited position reference signal as in Equation (6).

$$r_{lim}^{[n]} = r_{lim}^{[0]} + \lim_{n\to\infty}\sum_{i=1}^{n}\left(\left(t^{[i]} - t^{[i-1]}\right)\underbrace{sat\left(\nu_{lim}^{[i-1]} + \left(t^{[i]} - t^{[i-1]}\right)a_{lim}^{[i]}\right)\Big|_{-\nu_{max}}^{\nu_{max}}}_{\text{Discrete-Time Integrator - Limited}}\right), i \in \mathbb{N} \tag{6}$$

where $r_{lim}^{[0]} = 0$ and $\nu_{lim}^{[0]} = 0$.

2.3. Velocity + acceleration + jerk limiter

In this filter type up to third order derivatives are limited so that the acceleration of trapezoid type is obtained for a step input reference signal. Because of trapezoid type of acceleration, S shaped velocity profile is obtained that also causes smoother reference trajectory compared to velocity+acceleration type filter. This filter has four steps as below.

- Velocity limitation loop : The exactly same loop is used as given in Section 2.1

- Acceleration limitation loop : The input of this loop is the limited velocity of the first loop. Similar derivative, saturation and integration steps are taken for the velocity input to obtain position data with a limited acceleration. Position is not fed back to system.

- Jerk limitation loop : Limited acceleration is the input for this step. Derivative, saturation and three successive integration with saturation is used to obtain jerk-limited reference.

- Correction action : Velocity data is used for correction action.

Finally, not only the third derivative but also all derivatives will have limitations so that for a step input an S shaped velocity profile is obtained with limitation. Velocity+acceleration+jerk limitation filter block diagram is depicted in Figure 4.

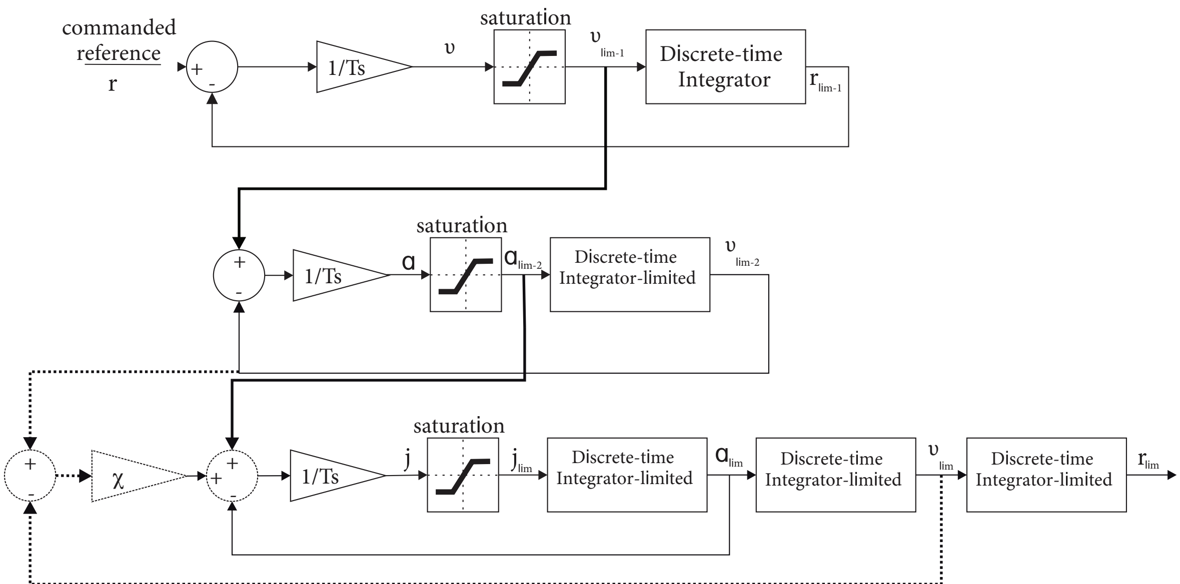


Figure 4. Jerk limiter block diagram.

The loop equation for the jerk limitation is given as follows.

$$j_{lim}^{[i]} = sat\left(\frac{a_{lim-2}^{[i]} - a_{lim}^{[i-1]} + \left(\nu_{lim-2}^{[i]} - \nu_{lim}^{[i-1]}\right)\chi}{t^{[i]} - t^{[i-1]}}\right)\Bigg|_{-j_{max}}^{j_{max}}. \tag{7}$$

The saturation function is applied for $\pm j_{max}$. $\chi \in \mathbb{R}^+$ is a constant and defined as $\chi = \frac{j_{max}}{a_{max}}$. Substituting this constant in Equation (7) and making some manipulations the following equation is obtained.

$$j_{lim}^{[i]} = sat\left(j_a^{[i]} + j_{max}\Psi^{[i]}\right), \qquad \Psi^{[i]} = \frac{a^{[i]}}{a_{max}}. \tag{8}$$

The filter uses three consequent discrete integrals in order to obtain the jerk + acceleration + velocity limited position reference signal as in Equation (9).

$$r_{lim}^{[n]} = r_{lim}^{[0]} + \lim_{n\to\infty} \sum_{i=1}^{n} \Bigg(\left(t^{[i]} - t^{[i-1]}\right) sat\Bigg(\nu_{lim}^{[i-1]} + \left(t^{[i]} - t^{[i-1]}\right) sat\left(a_{lim}^{[i-1]} + \left(t^{[i]} - t^{[i-1]}\right) j_{lim}^{[i]}\right)\Bigg|_{-a_{max}}^{a_{max}}\Bigg)\Bigg|_{-\nu_{max}}^{\nu_{max}} \Bigg) \quad (9)$$

where $i \in \mathbb{N}$, $r_{lim}^{[0]} = 0$, $\nu_{lim}^{[0]} = 0$ and $a_{lim}^{[0]} = 0$.

3. Simulation studies and comparison of the results

In this section, the effectiveness of the proposed filters, designed in Section 2, will be investigated by numerical simulations. The results are compared with the previous study's results and it is shown that the proposed method is superior to the method proposed in [16].

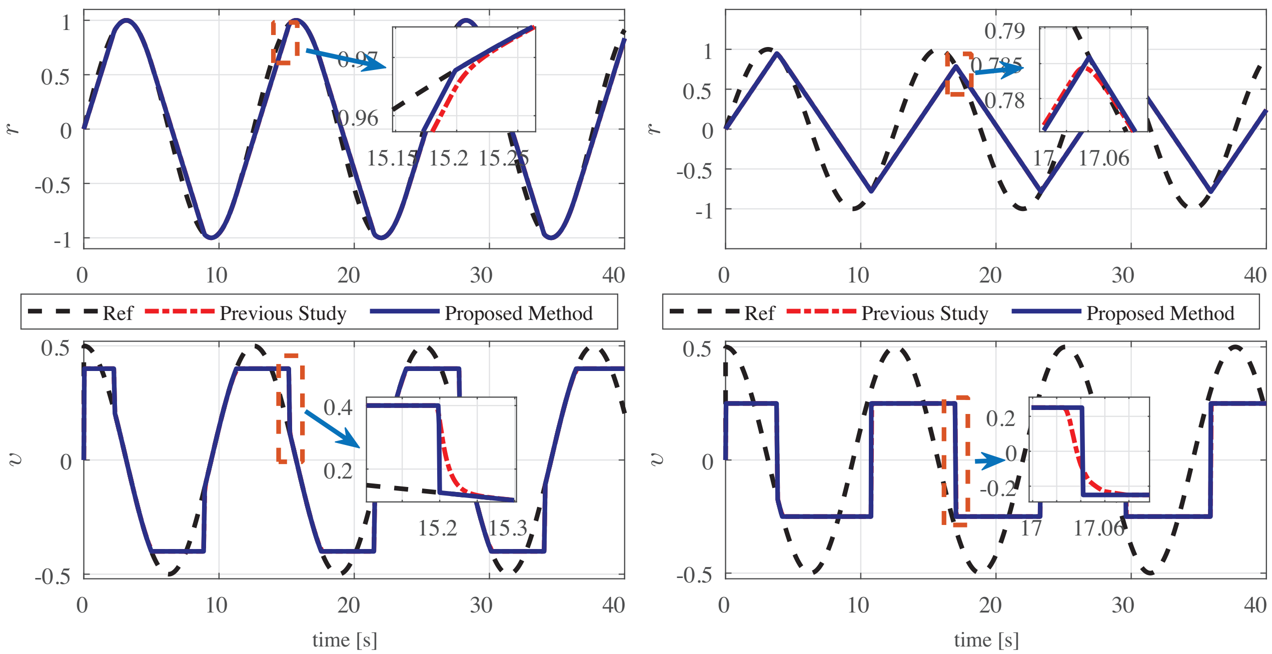
A fixed step 4^{th} order Runge–Kutta ODE solver (ode4 in Simulink) is used for the simulations where the step size T_s is chosen to be 1000 samples per second. Although our method is designed for discrete time, the previous study has continuous states; therefore, to run them both in the same simulation environment, fixed step continuous-time solver is chosen. Velocity, acceleration and jerk of the reference signal and filtered outputs are obtained by taking the sequential derivatives.

First of all, the velocity limiter results will be presented for sine wave and step signals. Figure 5 shows the responses of the velocity filter for the reference signal $r(t) = sin\left(\frac{1}{2}t\right)$ [16]. Without velocity limitation, both methods show good response to track the given reference signal $r(t)$. If a velocity limitation of 80% of the maximum velocity value is introduced, as shown in the ν plot in Figure 5a, the velocity value is saturated at the chosen value, and this saturation continues even after the velocity value of the reference signal $r(t)$ comes back below the saturation limit. By this way, the reference signal can be followed as close as possible at a shortest time. The proposed filter follows the reference signal much closer compared to the previous study's result. The sub axis in reference plot between 15.1 and 15.3 s shows closer view of the reference tracking.

For the same reference signal, Figure 5b shows the response of the filter for a velocity limitation of half of the maximum velocity value. This creates a discontinuous change in velocity that results in a triangular shaped reference output. In the ν plot, the velocity limitation is satisfied for both the previous study and the proposed method; however, the proposed method makes it in such a way so that it catches the reference signal quicker and tries to follow it.

The response of the velocity filters to step inputs is depicted in Figure 6. Similar to the sine wave response, proposed method presents a better performance and catches the reference signal with the active velocity limitation. Actual velocity of the step signal depends on the sampling period T_s. Therefore, a step signal with an amplitude of $5\,units$ has $\nu_{max} = 5000\,units/s$ for $T_s = 0.001s$. In the first simulation, velocity is limited to $100\,units/s$. As seen from Figure 6a, while the proposed method holds the velocity constant until the reference signal is reached, the method introduced in the previous study cannot provide a constant velocity profile. Therefore, for the previous study it takes longer to catch the reference signal. Increasing the velocity limit to $500\,units/s$, things get worse for the previous method, and the reference signal is caught much later with an unwanted velocity profile as shown in 6b.

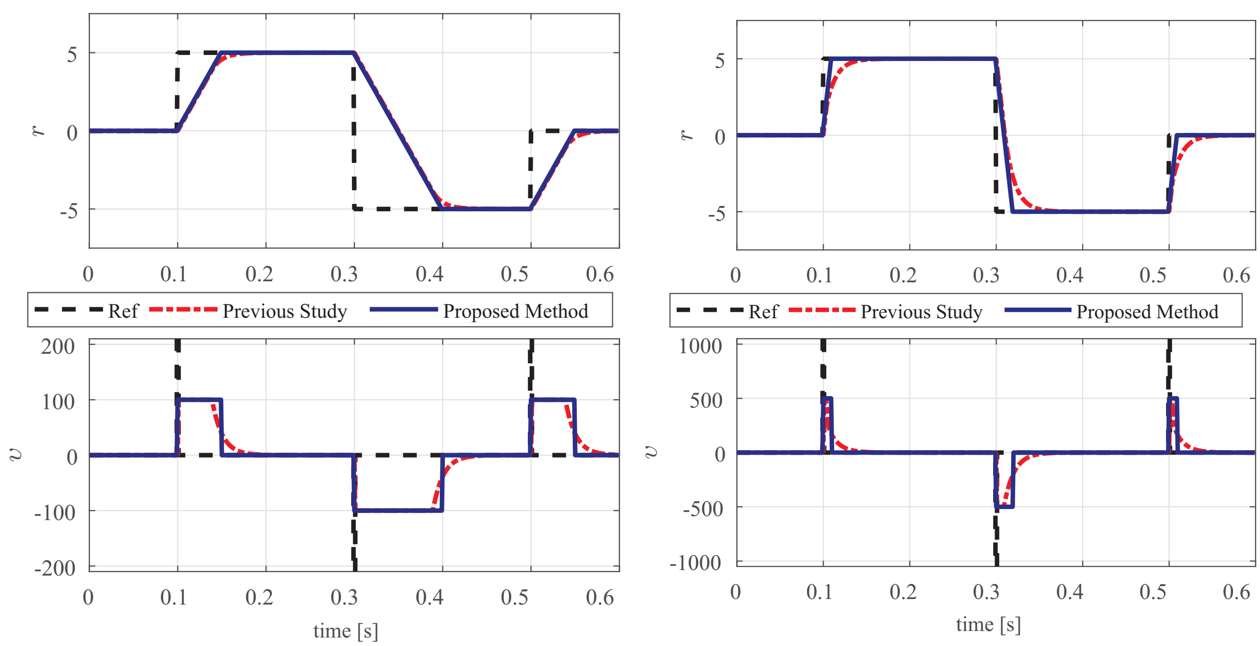
Acceleration limitation filter response to sinusoidal input is given in Figure 7. The sinusoidal input is



(a) Velocity Limit = 0.4

(b) Velocity Limit = 0.25

Figure 5. Velocity limiter response to sinusoidal type input.



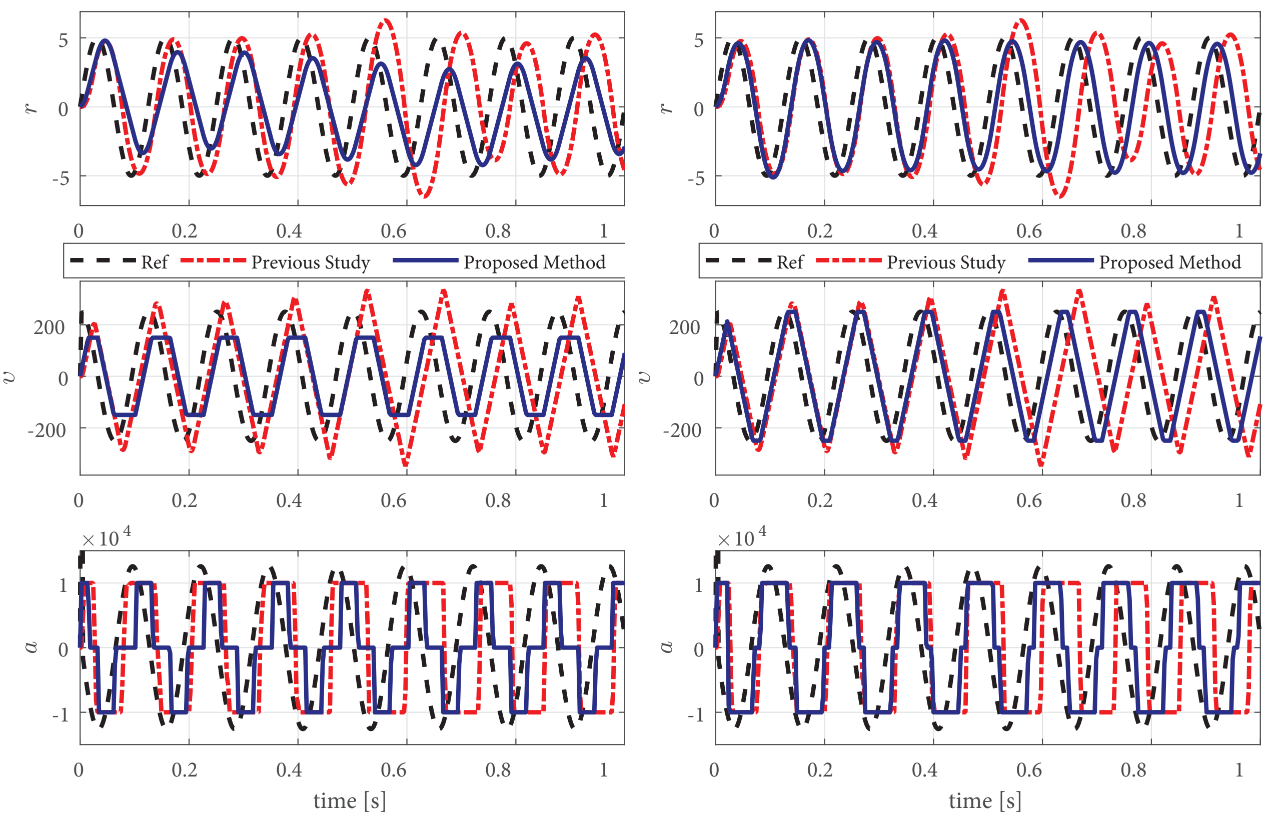
(a) Velocity Limit=100

(b) Velocity Limit=500

Figure 6. Velocity limiter responses to step input for different rate limits.

set to $8\,Hz$ frequency with an amplitude of $5\,units$. With the sampling period of 1000 samples per second, maximum acceleration of this signal is obtained $93965\,units/s^2$ at the initial movement and settles to max

12613 $units/s^2$ for sinusoidal change. Maximum velocity of the reference signal is 251 $units/s$ in positive and negative direction. In the first simulation, acceleration is limited to 10000 $units/s^2$ and velocity is limited to 150 $units/s$ and the responses are shown in Figure 7a. In the second simulation, whose response graphs are given in Figure 7b, acceleration limit is kept the same and the velocity limit is chosen to be 250 $units/s$. Increasing the velocity limit improves the signal following performance of the proposed filter. In both of the simulations acceleration and velocity is saturated in a successful manner with the proposed filter. The method proposed in [16] performs a strange behaviour at 0.5 $second$, and after that point phase shift occur in the response. Although the acceleration filter is satisfied, velocity is not filtered in the previous study.



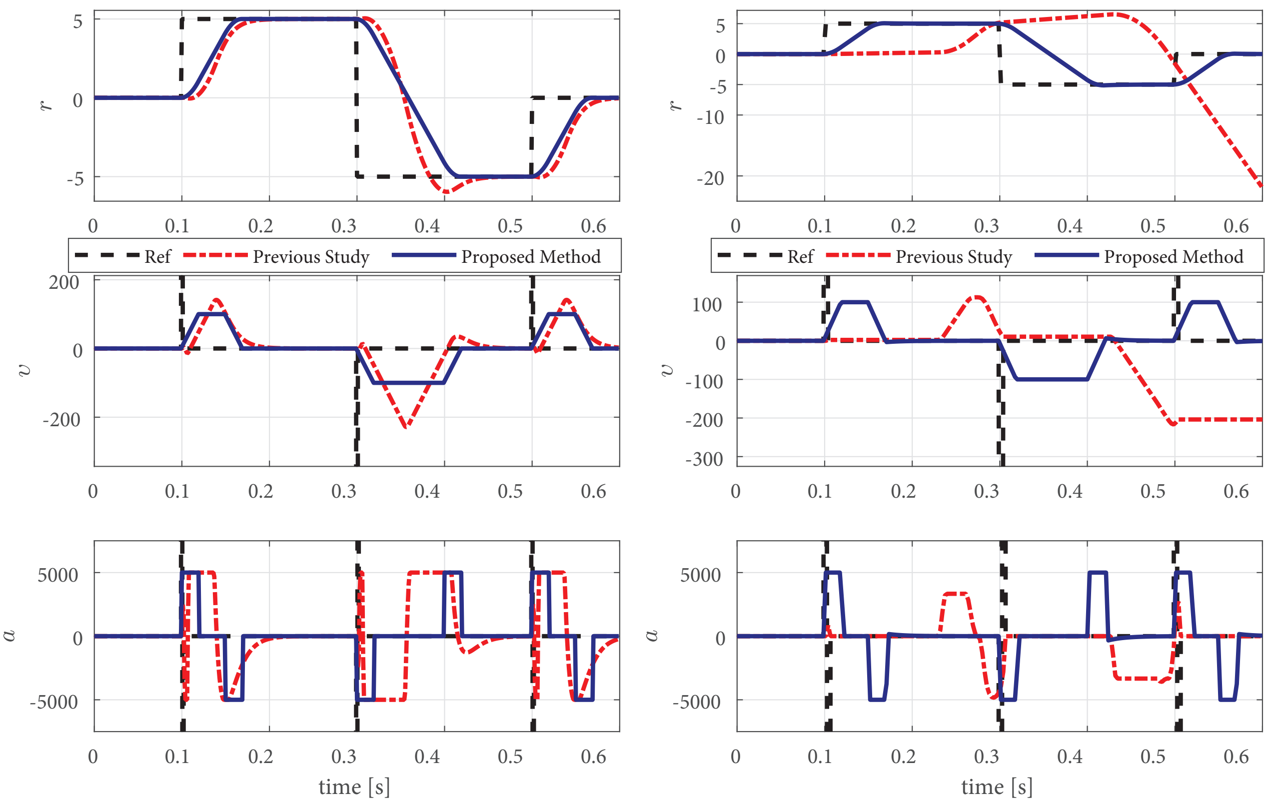
(a) Velocity Limit = 150

(b) Velocity Limit = 250

Figure 7. Acceleration filter response to sine input for different velocity limitations.

Step reference response of the acceleration input is shown in Figure 8. Velocity saturation limit of 100 $units/s$ and acceleration limitation of 5000 $units/s^2$ are used in the simulations. Figure 8a shows the response of the filters with 0.001s time step in the solver. Proposed method can successfully saturates acceleration and velocity at the same time, and smooth reference is obtained. Previous study's method concludes an improper response with undershoot and overshoots and does not saturate the velocity at the same time as well. Higher time steps for the solver does not change the response of the proposed filter. On the other hand, the previous study's response becomes unstable as shown in Figure 8b.

Since the jerk limiting filter is not proposed in [16], the proposed method's behaviour will be given without performing a comparison. Figure 9 shows the step response of the proposed jerk+acceleration+velocity limita-



(a) Sampling Frequency = 1000 samples/second

(b) Sampling Frequency = 375 samples/second

Figure 8. Acceleration filter response to step input for different sampling frequencies.

tion filter. Velocity limit of $200\,units/s$, acceleration limit of $8000\,units/s^2$ and jerk limit of $1200000\,units/s^3$ is satisfied and as a result an S shaped smooth output is obtained.

Comparison of the three proposed filters are given in Figure 10 for the step responses. Velocity limiter is the fastest as the acceleration is not limited then acceleration limiter is faster than the jerk limited response since the jerk is not limited in this filter. All of the filters have the same velocity limitation; therefore, they have a flat behaviour at rising region. Slowest response is obtained by jerk limited signal response. However, it can be made as fast as the acceleration input by increasing the jerk limitation value and same comment holds for acceleration filter, which can be made faster as well by increasing the acceleration limit value.

4. Real time application

For the real time application of the proposed rate limiting schemes, a missile fin actuation system's position controller is used as an example. Fin actuation system fundamentally consists of an electric motor, power train (in this case a ball screw), bearings and a position sensor as shown in Figure 11.

Rotary motion in the electric motor is converted to linear motion on the screw part, and this linear motion is converted back to rotary motion again at the stage where the fin is connected. Equation of motion of this system can be defined as a second order linear system with the structure given in the following equation

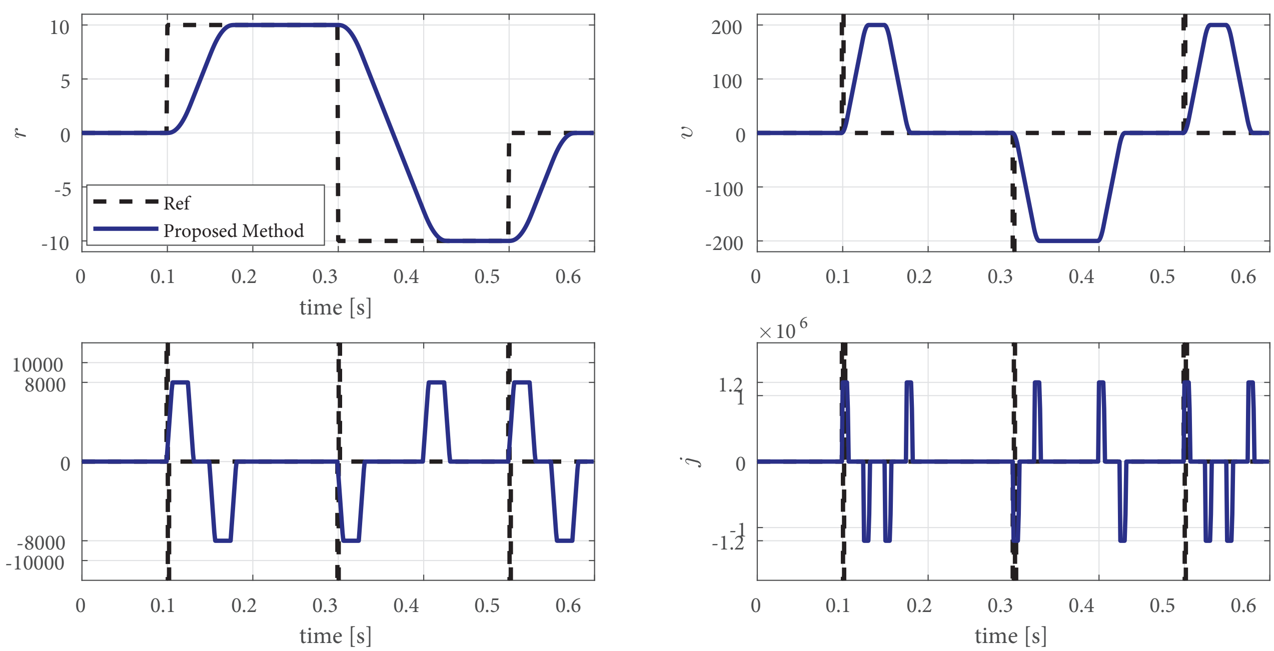


Figure 9. Jerk limiter step reference response.

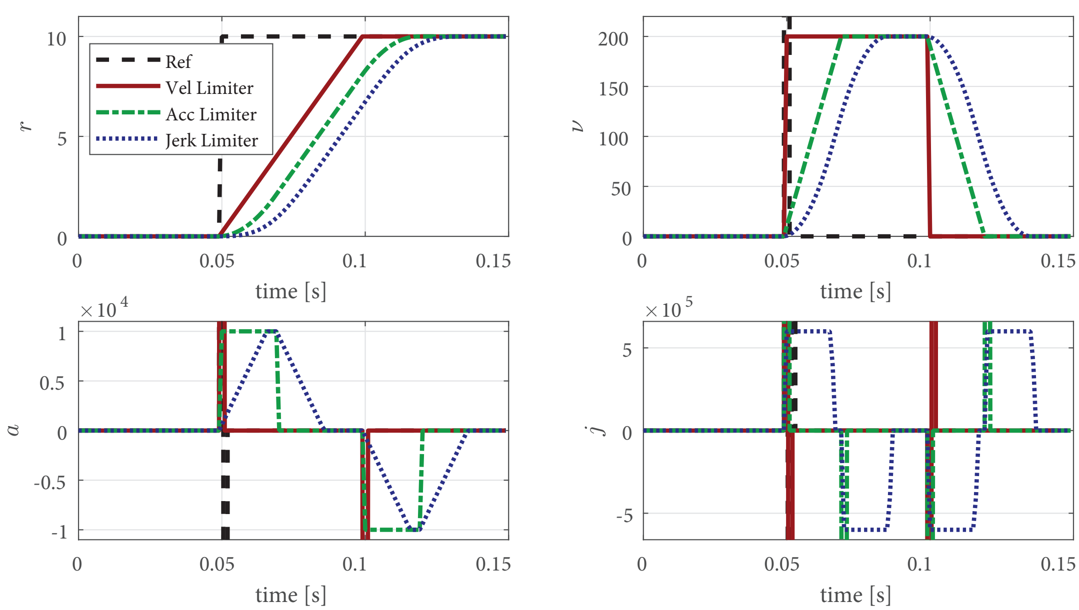


Figure 10. Comparison of step reference responses of the 3 proposed filters.

and for this model, linear or non-linear many control techniques can be designed and applied.[1]

$$\frac{Y(s)}{U(s)} = \frac{K_t}{Js^2 + Bs}, \tag{10}$$

[1]Helix Linear Technologies, Missile Fin Actuation System Case Study [online]. Website https://www.helixlinear.com/media/10483/missile-fin-actuation-case-study-1.pdf [accessed 09.05.2021]

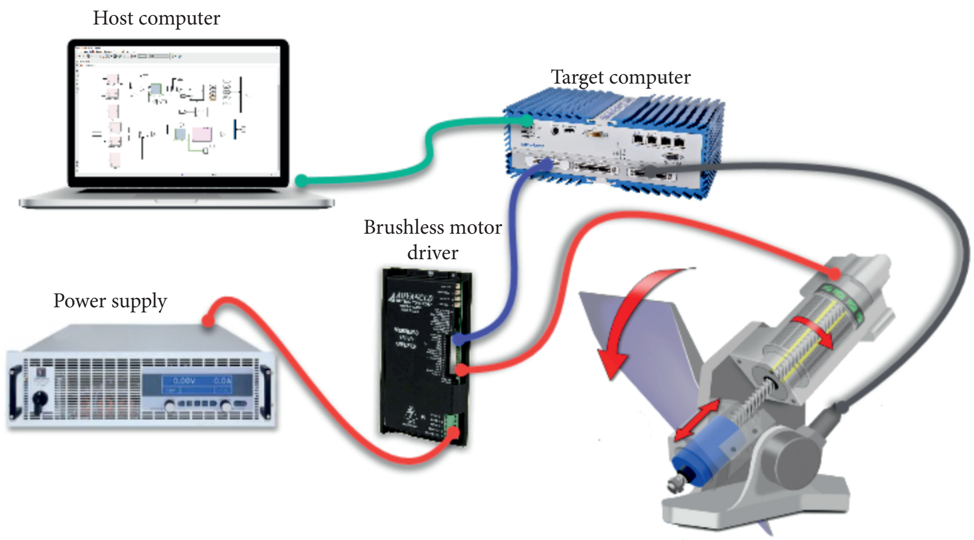


Figure 11. Real time application test setup visualisation (fin actuation system visual from) [1]

where $K_t = 19.5\ \frac{Nm}{A}$, $J = 0.32\ kg \cdot m^2$ and $B = 8.25\ \frac{Nm \cdot s}{rad}$, respectively stands for equivalent torque constant, equivalent inertia and equivalent viscous friction at the fin's output.

In this study, author wants to show the effectiveness of the rate limiting filters; therefore, the details of the controller and the actuation systems model will not be given in detail since the designed rate limiting filters are model independent. Control action is calculated using the feedback measured from the fin actuation system's rotary sensor and commands are sent back to the electric motor via brushless motor driver. This process is depicted in Figure 11.

Rate limiting filters are designed in discrete time; therefore, sampling period of $0.001s$ is chosen for real time applications with discrete time solver. By this way, discrete time performance of the proposed method is validated in addition to continuous time response given by simulations. Controller responses for step input reference signal is tested first, then velocity, acceleration and jerk limiting filters are applied, respectively. As there is no reference generator from guidance computer in the laboratory, predetermined step signals are created and applied in real-time. The responses of the fin actuation system to the step signal reference and rate limited reference signals are given in Figure 12. For the simulations $10\,degrees$ of step fin deflections in both direction is applied. For the velocity filter $200\,deg/s$ limitation is used. Acceleration limitation of $20000\,deg/s^2$ is used together with the velocity limitation. Finally, jerk limitation of 100 times of the value of the acceleration limitation is used additionally the same acceleration and velocity limitation values are used for the jerk limitation.

Without any rate-limiting filter, the response of the system to pure step signal is inefficient and makes high overshoots. Velocity filter dramatically drops the overshoot value and acceleration and jerk limitations provide some more improvements for the overshoot value as well. As all of the filters have the same velocity filter property, they provide constant velocity profile as shown in detail in Figure 12. Current consumption in closed loop for each filter type and step reference are given in Figure 13.

Control action for the step input signal is limited by the power supply threshold value. Due to this limi-

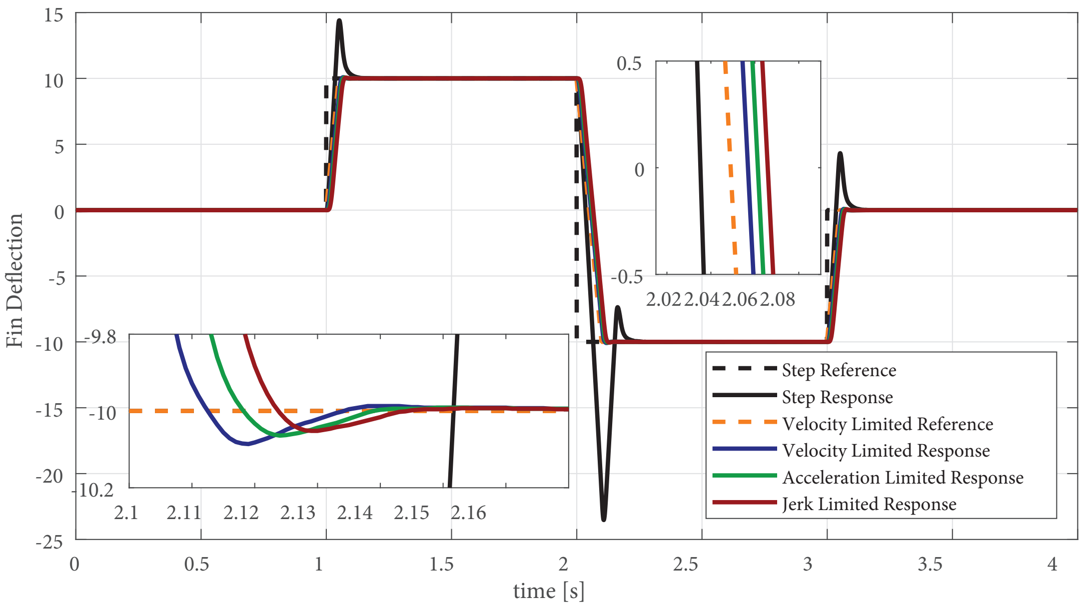


Figure 12. Fin actuation system response to four different reference commands [degs].

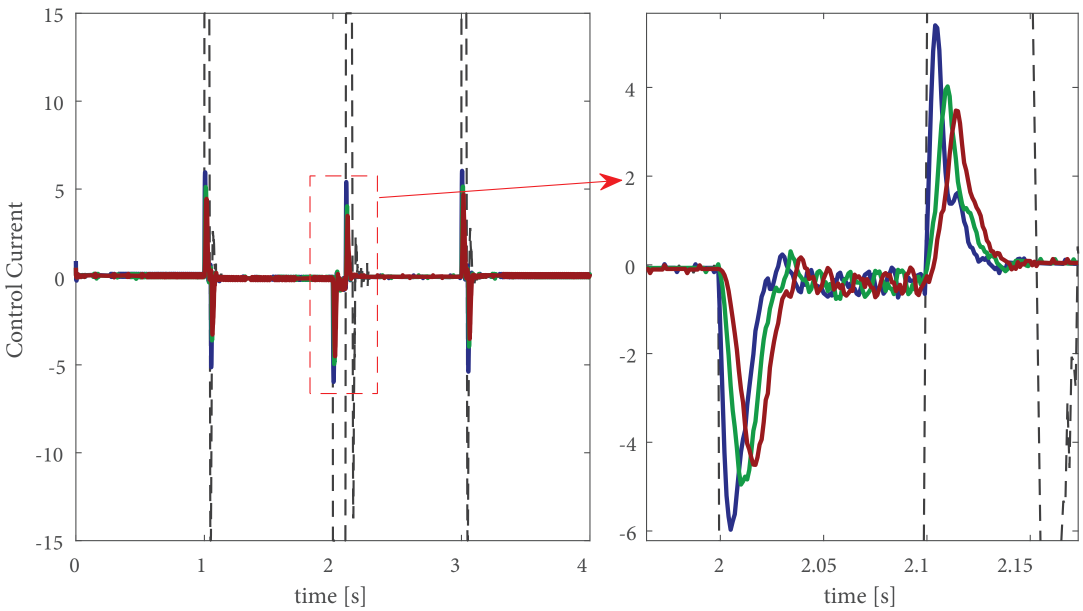


Figure 13. Real time control input - current [A].

tation, controller cannot pull the system back from the overshoot when it goes from $10\,degrees$ to $-10\,degrees$ and the system almost hit the mechanical limit of the system which is at $25\,degrees$. All of the filters proposed in this study prevents high current consumption, and, because of less overshoot values, they also prevent mechanical impact. Avoiding the mechanical impact is very important otherwise a breakdown may happen in the system. If these filters are not used, it is impossible for the system to respond to the order of $20\,degree$ step angle in a manner that will not damage the system.

Velocity profile for the responses of each filter and step input is given in Figure 14. As seen from the figure step response angular velocity exceeds $300\,deg/s$, while responses to filtered references settle to limited velocity value of $200\,deg/s$ with a low overshoot in the velocity.

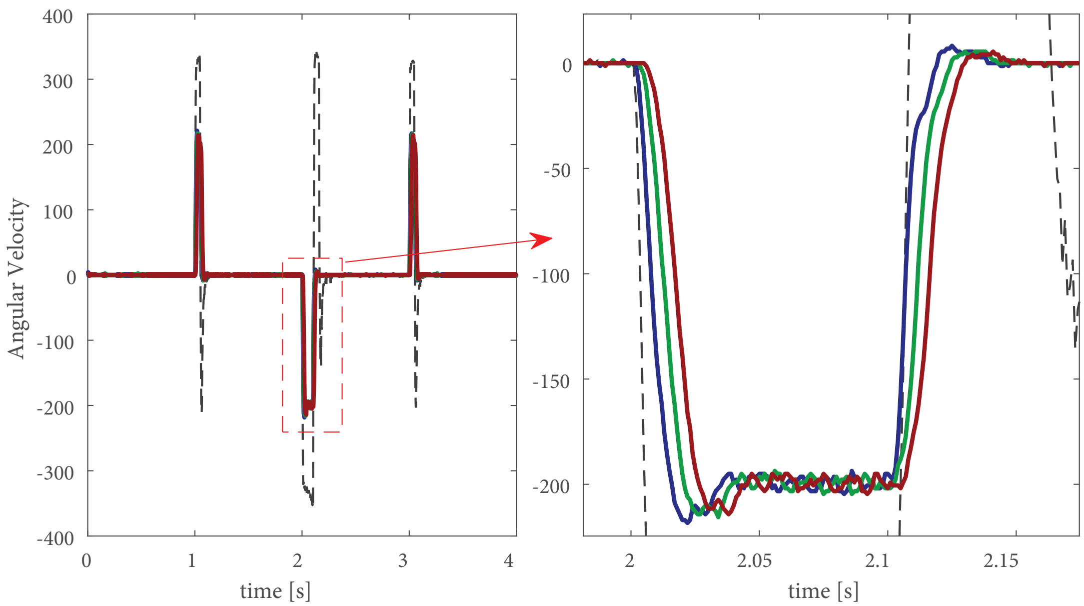


Figure 14. Real time angular velocity [deg/s].

Table gives a comparison of some properties of the response signals and the control signals.

Table . Performance comparison of the response of the system to proposed filters.

Methods	Overshoot $[deg]$	Settling time (2%) $[ms]$	Max current $[A]$	RMS current $[A_{rms}]$	Max elocity $[deg/s]$
No Limit	13.5238	208	15	3.7756	357.0557
Velocity Limit	0.0902	108	6.0375	0.6139	221.0999
Acc+Vel Limit	0.07224	113	5.1428	0.5517	216.9800
Jerk+Acc+Vel Limit	0.0559	118	4.6967	0.5205	214.2334

One can see from the table that the proposed rate limiting filters significantly improve the performance of the control system. They reduce the overshoot compared to step response. Although maximum velocity is achieved by step response, proposed filters provide faster settling times. Settling time with filters are reduced almost half of the one achieved by the step response. Respectively for velocity, acceleration and jerk constraints $48.08\%, 45.67\%, 43.27\%$, improvements in settling times are achieved.

Control current hits the saturation limit in the case of step response. Velocity limiting itself reduced this value 59.75%, acceleration limiting provides 14.82% improvement over the velocity filter and jerk limiting provides extra 8.67% reduction over acceleration limitation. Avoiding control input saturation is so important in case an external disturbance or parameter changes may cause the system to be unstable. Disturbance rejection requires high gain in the controller that can further be increased using the proposed filters if step like commands are expected in the reference.

For the evaluation of the power consumption throughout the entire run, we can have a look at the RMS current consumptions. Reduction of 83.74% power is attained by velocity limitation. Acceleration limitation reduces 10.130% over the velocity limitation and acceleration limitation contribute further 5.66%.

Maximum velocity is limited in the proposed filters; however, because of the overshoot in velocity, higher values are reached. Velocity values are calculated using discrete derivative of the fin deflection output; therefore, some glitches are observed. Either case responses with filters settles to the required $200 deg/s$ value without going beyond too much. Velocity response to unfiltered step is almost equal to the theoretical no-load speed of the system that is 367.7419 $\frac{deg}{s}$. At this point, electric motor can provide a little torque, which is consumed for friction, etc., whereas, if an external disturbance torque exerts on the fin's surface, the system unfortunately cannot respond to that disturbance effects and the system may go into instability. Additionally, higher speed in the system increases the voltage requirement as well.

5. Conclusion

In this study, three rate limiting schemes are introduced, which can be implemented without changing the existing design of the controller. They can be placed just after the reference command before feeding it to the controller, and, hence, the reference rates are filtered as required.

In the previous studies, designed rate limiters only limit one property at a time, while proposed rate limiting filters take simultaneous rate limiting into account; therefore, for example, acceleration and velocity can be limited at the same time. This is an important property so that the velocity for an electric motor controlled in a matter without exceeding the voltage requirements. As for missile systems, power consumption is a big concern and low mass, small volume power supply systems with limited power capacity is used, and one expects from the subsystems to use the resources as low as possible. Limiting the velocity decreases the voltage requirement and decreasing the inertial forces by smoothing rapid movement requirement, current consumption might be scaled down. Due to reduced accelerated inertial movements, there will be a decrease in the force or torque values in the drivetrain; thus, smaller and lower cost products can be used as well.

As shown in the real time application section, due to aggressive motion and high overshoots, mechanical system may be damaged, which may also cause consequent problems in the connected upper assembly such as missile instability in this case.

Previous studies provide rate-limiting filters with tunable parameters, which need to be tuned depending on the input signal. That makes it difficult for a random generated signal set for these filters. However, proposed filters can cope with these random signals by making correction parameters formulated via limit values. The other important advantage of the proposed filters is that they are not model dependent, whereas you need a system model in most of the other methods mentioned in the introduction.

Finally, without changing the existing design of the controller, one can reduce the energy consumption or choose lower price products for the system as the force and torque requirements will be lowered as a consequence. On the other hand, low gain controllers due to step inputs can be improved for better disturbance rejection as the error rate of change can be made smaller with the proposed filters.

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