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Preliminary Design of Spacecraft Attitude Control with Pulse-Width Pulse-Frequency Modulator for Rest-to-Rest Maneuvers

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In this paper, the preferred region of design parameters for quasi-normalized equations of single-axis attitude control of rigid spacecraft using pulse-width pulse-frequency modulator (PWPFM) is presented for rest-to-rest maneuvers. Using the quasi-normalized equations for attitude control reduces the system parameters, that is, the moment of inertia, the filter gain, and the maximum torque of modulator are merged to other parameters and the total number of parameters is reduced. Therefore, the computational burden is decreased and moreover, the results are usable for grouped parameters, regardless of the value of each parameter separately. The optimization is carried out by grid search method with the performance index of fuel consumption or number of thruster firings for a range of inputs. Finally, the suggested upper and lower bounds of parameters are obtained based on the optimization results.

Keywords: Spacecraft Attitude Control, Pulse-Width Pulse-Frequency Modulator, Quasi-Normalization, Optimization

Introduction

There are several techniques for attitude stability and maneuver of a spacecraft, including continuous and discontinuous control methods [1]. On-off thrusters are used in applications where the torque needed for control is greater than the torque produced by continuous devices [2]. There are numerous studies in designing the spacecraft control systems actuated by on-off thrusters [3-6] in which pulse modulation thrusters are the most commonly used techniques.

The simplest on-off control technique utilizes the bang-bang controller. To eliminate the pulse chattering behavior, bang-bang with dead-zone controller has been introduced [7,8]. To enhance the performance of the bang-bang controller with dead-zone, some hysteresis is usually added referred to as Schmitt Trigger. Besides, there are some modulators composed of a Schmitt Trigger, e.g., Pulse-Width Pulse-Frequency Modulator (PWPFM) and Pseudo Rate Modulator (PRM). PWPF and PR modulators are composed of a Schmitt Trigger, a first-order filter, and a feed-back loop. In PWPFM, the filter is in the feed-forward loop, opposed to PRM, in which the filter is in the feedback loop [1]. PWPFM is the most prominent modulator due to its numerous advantages, such as high precision and low fuel consumption in spacecraft attitude control [9,10]. The PWPFM is also used for other applications such as kinetic kill vehicles [11].

The important issue in spacecraft attitude control based on PWPF modulator is the proper setting of the parameters, as improper settings would cause high fuel consumption and thruster firings, large output phase lag, and even instability of the system [11]. There are several works dedicated to this matter, for both rigid [12] and flexible spacecraft [13,14], but the results are obtained only for a specified value of attitude angle command and spacecraft specification.

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Several of PWPFM designs using variable structure control [15], sliding mode control [16], and adaptive control [17], utilized the preferred region of PWPF parameters, have been obtained in Ref. [14].

Recently, the preferred regions of parameters for PWPF and PR modulators have been determined using grid search method and their performance has been compared, but again only for a specified attitude command and predetermined spacecraft specifications [18,19]. Hence, if the specified values change - i.e. attitude command, thruster torque, and spacecraft moment of inertia - the optimization must be repeated. Using the quasi-normalized equations of attitude control with PWPF, introduced in Ref. [20], the total number of grouped parameters is reduced for the purpose of optimization. In addition, the preferred regions can be obtained in a quasi-normalized form, regardless of the values of each parameter, such as moment of inertia and filter gain, as treated in Ref. [21].

The objective of this study is to present the preferred region of PWPF parameters in a quasi-normalized form. In this regard, the static and dynamic simulations are first carried out and the system analyses are presented for a rest-to-rest maneuver. Then, the quasi-normalized parameters are optimized for a range of attitude angle inputs.

PWPFM in Quasi-Normalized Form

The single axis control system based on PWPFM with attitude and rate feedback for a rigid spacecraft is depicted in Fig.1. As shown in this figure, besides the reference input (Θ_{ref}) and the initial conditions, the system consists of 8 parameters, including maximum torque of Schmitt Trigger (U_m), hysteresis on threshold (U_{on}), hysteresis off threshold (U_{off}), filter gain (K), filter time constant (T_f), spacecraft moment of inertia (J), attitude feedback gain (K_x), and velocity feedback gain (K_{xd}). These parameters should be chosen so that the overall performance of the control system is desirable. Finding the preferred interval for each parameter requires multiple cost and time consuming simulations and therefore, reducing these parameters is a useful and efficient solution.

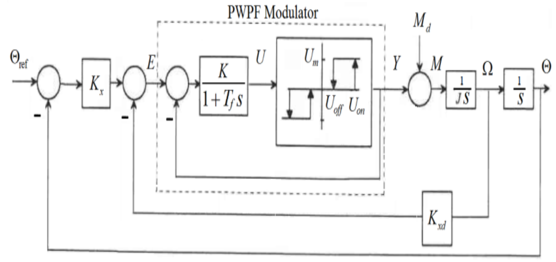

Figure 1. Block diagram of PWPFM in single axis attitude control for rigid spacecraft [1]

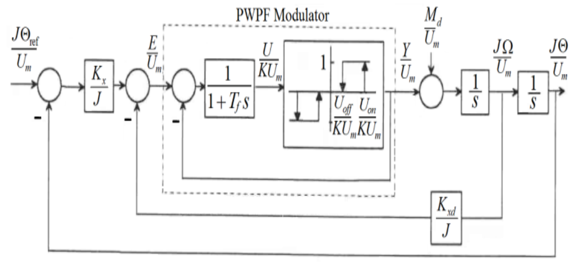

Figure 2. Quasi-normalized block diagram of PWPFM in Figure 1 [20]

As shown in Figure 2, by merging the moment of inertia, the filter gain, and the maximum control torque in other parameters, the attitude control block diagram can be expressed using grouped parameters of U_{on}/KU_m, U_{off}/KU_m, K_x/J, K_{xd}/J, and T_f.

Parameter Optimization

Here, the static, dynamic, and system optimizations are carried out to find the desired range of U_{on}/KU_m, U_{off}/KU_m, and T_f. The update command frequency of PWPF is taken 50 Hz. First of all, the three mentioned parameters are optimized and subjected to thruster firings or fuel consumption as the performance index. Due to our simplification assumptions, an interval is then suggested for each parameter by eliminating the upper 30% bound of the performance index. For example, in Fig. 3, the maximum number of thruster firings is 231; therefore, the region in which the number of thruster firings is 161 or lower is chosen. It should be noted that, the static and dynamic analyses are simulated for 20 seconds. System analysis simulations terminate when attitude error/reference angle<0.02 and $J\Omega/U_m$<0.02 rad·s or the time exceeds 20 seconds.

Static Analysis

In static analysis, a constant input is fed to the PWPFM and the performance of the modulator is studied with respect to thruster firings and fuel consumption. The input is chosen approximately in the middle of the modulator operating range, i.e., 0.5. Having fuel consumption as the performance index, the optimum values are $U_{on}/KU_m|^*$=0.48, $U_{off}/KU_m|^*$=0.46, and T_f^*=0.82; and regarding thruster firings as the performance index, the optimum values become $U_{on}/KU_m|^*$=0.06, $U_{off}/KU_m|^*$=0.02, and T_f^*=0.12. Using $U_{on}/KU_m|^*$, the simulations are done by varying U_{off}/KU_m and T_f, as depicted in Figure 3, and the undesired regions of U_{off}/KU_m and T_f are eliminated, i.e. the region which results in the upper 30% of performance index. This procedure is repeated for U_{on}/KU_m and T_f with fixed $U_{off}/KU_m|^*$ and also for U_{on}/KU_m and U_{off}/KU_m with fixed $T_f|^*$. The overall results are presented in Table 1 and some of the simulation results are depicted in Figures 3 and 4. As it can be seen in Fig. 3, $0.16<U_{on}/KU_m$ and $0.14<T_f$ are suggested regarding thruster firings and based on Fig. 4, $0.02<U_{off}/U_{on}$ and $0.02<T_f$ are preferred regarding fuel consumption. It should be noted that the upper bound of 0.5 on U_{on}/KU_m is exerted due to choosing the input equal to 0.5 and by changing the input, this bound is also changed. In other words, as long as the input has not reached the on threshold value, the modulator would not start.

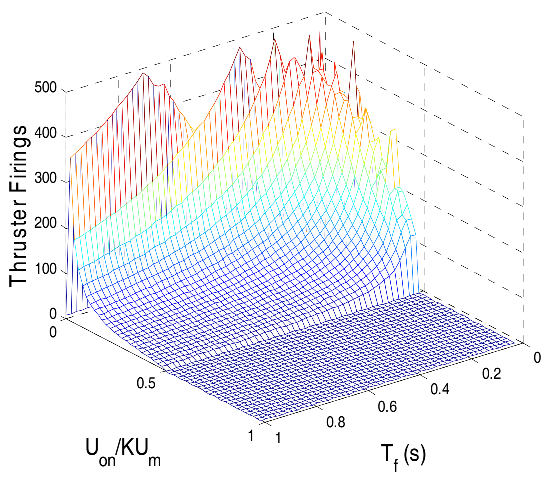

Figure 3. Thruster firings versus U_{on}/KU_m and T_f for $U_{off}/U_{on}|^*$=0.02

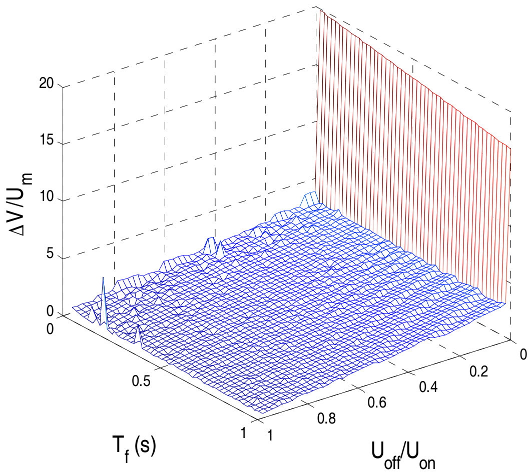

Figure 4. Fuel consumption versus U_{off}/U_{on} and T_f for $U_{on}/KU_m|^*$=0.48

Table 1. Suggested range of PWPFM parameters in static analyses

Performance Index	U_{on}/KU_m	U_{off}/U_{on}	T_f
Thruster Firings	0.16→0.5	0.02→0.96	>0.14
Fuel Consumption	0.02→0.5	>0.02	>0.04
Both Criteria	0.16 →0.5	0.02 →0.96	>0.14

Dynamic Analysis

In dynamic analysis, a sine wave is usually chosen as the input of the modulator. Here, the frequency of the sine wave is given between 1 to 150 rad/s and its amplitudes are set to 1. For each performance index, three graphs are produced. To obtain the desired intervals, first, U_{on}/KU_m and U_{off}/KU_m are set to the optimum values from the static analysis as the initial guess for the problem. Then, the performance index is computed in terms of T_f and the sine wave frequency, as shown in Fig. 5. As mentioned before, the preferred interval for T_f is chosen below the 30% of the maximum value of the computed thruster firings as the performance index. It should be noted that, Fig. 5 concerns the final stage graph and not the case for the initial guesses. Similarly, the preferred intervals for other parameters, e.g., U_{on}/KU_m and U_{off}/KU_m are obtained for the desired performance index. As shown in Fig. 5, the interval $0.09<T_f$ is chosen regarding thruster firings and based on Figure 6, the interval $0.55<U_{on}/KU_m$ is preferred regarding fuel

consumption. The overall dynamic analysis results are outlined in Table 2.

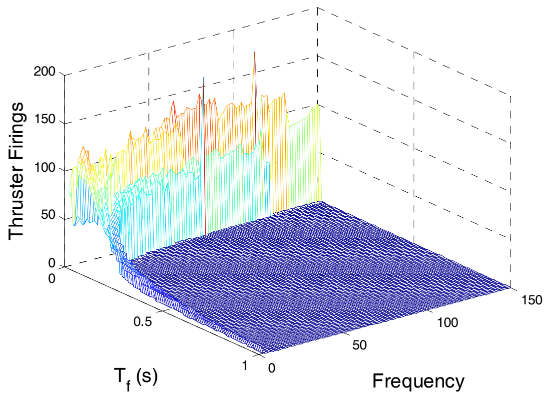

Figure 5. Thruster firings versus T_f and input frequency for U_{on}/KU_m=0.42 and U_{off}/U_{on}=0.7

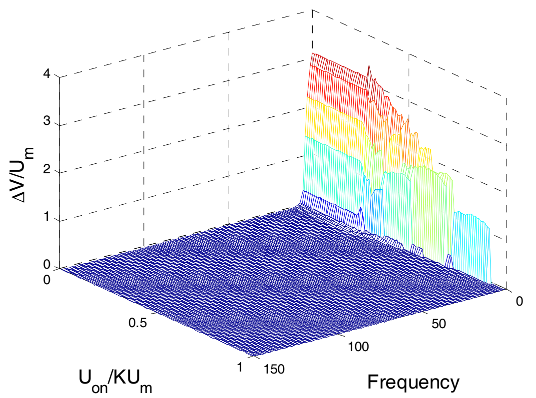

Figure 6. Fuel consumption versus U_{on}/KU_m and input frequency for T_f=0.42 and U_{off}/U_{on}=0.7

Table 2. Suggested range of PWPFM parameters in dynamic analyses

Performance Index	U_{on}/KU_m	U_{off}/U_{on}	T_f
Thruster Firings	> 0.33	<0.9	> 0.15
Fuel Consumption	>0.55	>0.27	>0.15
Both Criteria	>0.55	0.27→0.9	>0.15

System Analysis

Static and dynamic analyses have suggested the preferred ranges of PWPFM parameters, though to have a more realistic understanding of the modulator behavior in the system, these ranges should be specified in the attitude control system. In our system analysis, the modulator behavior is investigated in a simple rigid spacecraft model for a rest-to-rest maneuver. In this case, the control system consists of a PD controller plus the PWPF modulator. There are two schemes to determine the PD gains. The first is to optimize them alongside the other three parameters, as treated in Ref. [21], and the second is to presume fixed values for the feedback gains. Here, the second scheme is applied and it is assumed that the system considerations exert a fixed damping ratio of 1.5 and a natural frequency of 0.7 to the system, when it operates in its linear range, resulting in the feedback gains of K_x/J=0.49 and K_{xd}/J=2.1.

The system is, first, studied for a quasi-normalized attitude command of $J\Theta_{ref}/U_m$=200 deg.s^2. For example, for a spacecraft with J=10 Kg.m^2 and U_m=1 N.m, an input of 200 deg.s^2 is equal to a reference attitude input of 20 degrees. Primarily, the optimum values of U_{on}/KU_m, U_{off}/KU_m, and T_f are computed. Since there are two sets of performance indices, there are two sets of optimum values. In the first set, the performance index is the number of thruster firings with the constraints of settling time 20 seconds and overshoot<15%, resulting in $U_{on}/KU_m|^*$=0.5, $U_{off}/KU_m|^*$=0.05, and T_f^*=0.9 seconds. For the second set, the performance index is fuel consumption with the same constraints on the first set, resulting in $U_{on}/KU_m|^*$=0.2, $U_{off}/KU_m|^*$=0.05, and T_f^*=0.6 seconds. It is obvious that if the constraints were ignored, the optimum values would have changed, resulting in lower values for performance index, as we shall see in the next section. By applying the optimum values as initial guesses, the simulations are carried out and the preferred intervals are obtained. All the graphs are not included here, but some parts of the results are shown in Figures 7 to 10.

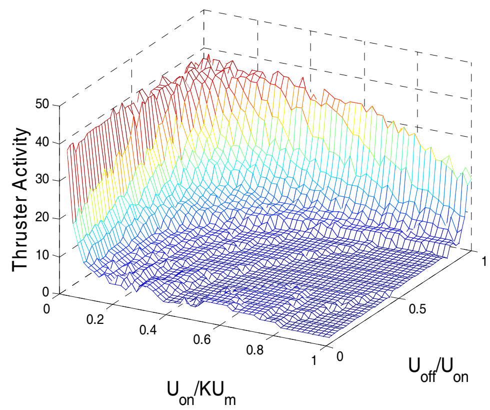

Figure 7. Thruster firings versus U_{on}/KU_m and U_{off}/U_{on} for T_f^*=0.9 (thruster firings as PI)

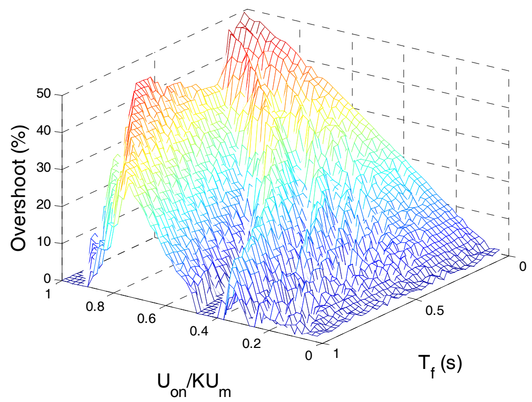

Figure 8. Overshoot versus U_{on}/KU_m and T_f for $U_{off}/U_{on}|^*=0.05$ (thruster firings as PI)

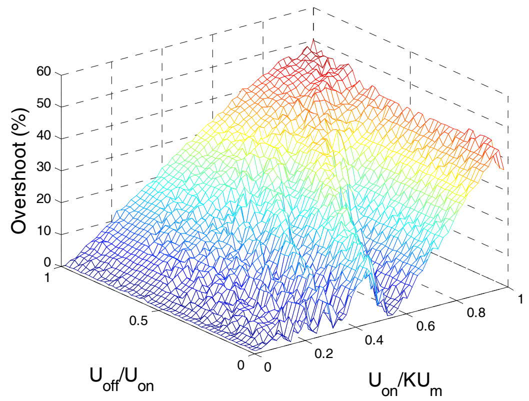

Figure 9. Overshoot versus U_{on}/KU_m and U_{off}/U_{on} for $T_f^*=0.6$ (fuel consumption as PI)

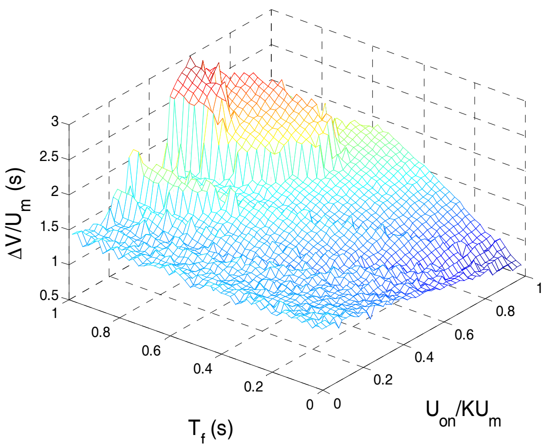

Figure 10. Fuel consumption versus U_{on}/KU_m and T_f for $U_{off}/U_{on}|^*=0.05$ (fuel consumption as PI)

For the first set, based on Fig. 7, intervals $0.14<U_{on}/KU_m$ and $U_{off}/U_{on}<0.82$ are suggested regarding thruster firings, and based on Fig. 8, intervals $U_{on}/KU_m<0.66$ or ($U_{on}/KU_m<0.66$ and $0.86<T_f$) are preferable regarding the output overshoot. For the second set, based on Fig. 9, interval $U_{on}/KU_m<0.64$ is suggested regarding the attitude overshoot. Also, regarding fuel consumption, based on Fig. 10, intervals $U_{on}/KU_m<0.48$, $0.86<U_{on}/KU_m$ or $T_f<0.6$ are suitable. However, the overall interval is chosen considering all the limiting bounds, as presented in Table 3.

Table 3. Suggested range of PWPFM parameters in system analyses

Performance Index	U_{on}/KU_m	U_{off}/U_{on}	T_f
Thruster Firings	0.24→0.62	<0.28	0.78→1
Fuel Consumption	<0.48	0.27→0.52	0.52→0.86

System Analysis for a Range of Inputs

The preferred regions of PWPF modulator parameters are acquired only for a specified value of quasi-normalized input angle, as mentioned before. Here, the preferred interval of PWPFM parameters are obtained for a range of quasi-normalized input angles, i.e., $J\Theta_{ref}/U_m$=50-250 deg.s^2, and the results can be viewed in Figures 11 to 16, computed for a step increment of 25 for the quasi-normalized input angle as shown by asterisks (*) in these graphs. The obtained points are connected by straight lines, only to show a behavioral trend.

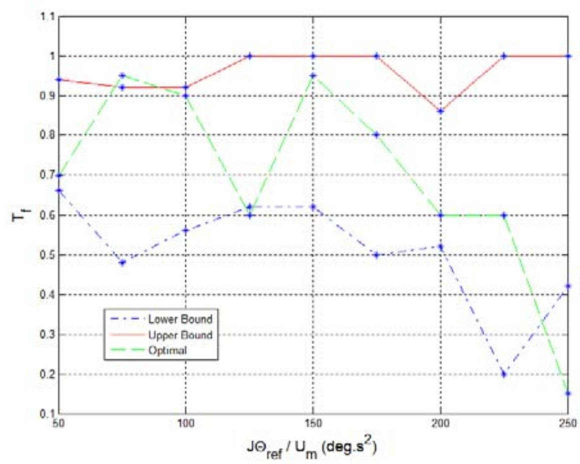

Figure 11. Suggested regions for T_f regarding fuel consumption

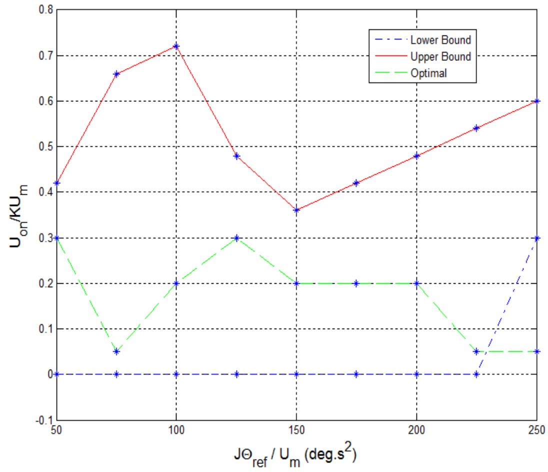

Figure 12. Suggested regions for U_{on}/KU_m regarding fuel consumption

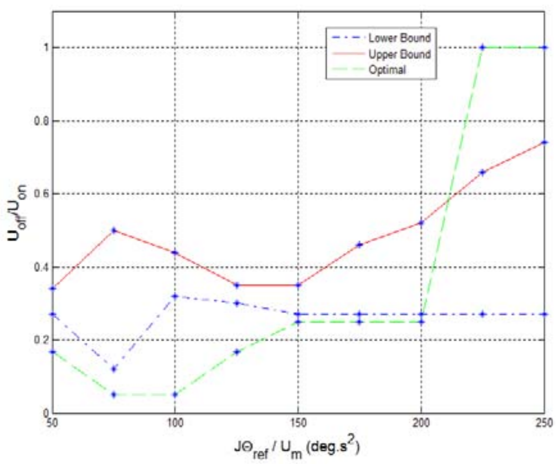

Figure 13. Suggested regions for U_{off}/U_{on} regarding fuel consumption

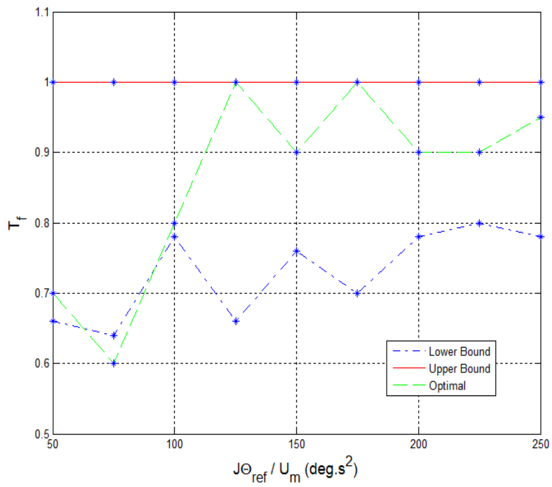

Figure 14. Suggested regions for T_f regarding thruster firings

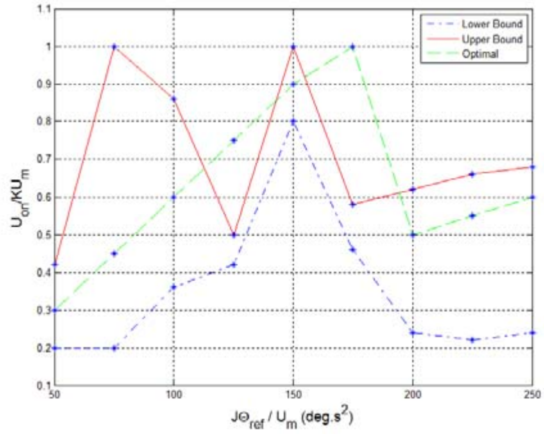

Figure 15. Suggested regions for U_{on}/KU_m regarding thruster firings

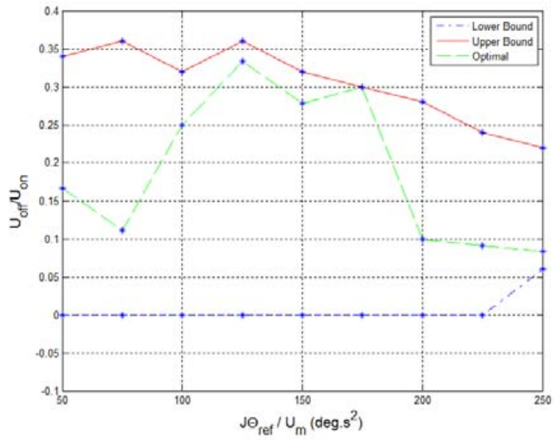

Figure 16. Suggested regions for U_{off}/U_{on} regarding thruster firings

It is clear that by decreasing the step increment of 25, the behavioral trend would be more accurate. The dash-dotted line is the lower bound limit, the solid line is for upper bound limit, and the dashed line in these graphs shows the optimum values.

Having fuel consumption as the performance index results in a larger range for T_f and U_{on}/KU_m than that for the thruster firings, as depicted in Figures 11 and 14 for T_f and Figures 12 and 15 for U_{on}/KU_m, respectively. Opposed to these two quasi-normalized quantities, the suggested interval of U_{off}/U_{on} becomes larger regarding thruster firings, as shown in Figures 13 and 16. As seen in these figures, there are some points in which the optimum values lay outside the suggested limits. This is because there are some small vicinity around the optimum values which have been removed from the final suggested bounds, since they are unreliable due to unmodeled dynamics and our simplifications. These graphs help us in the preliminary study of the attitude control systems using PWPFM. Based on the application, one can choose the suitable value of each parameter regarding fuel consumption or thruster firings. It is worth noting that large values of T_f cause undesired system phase lag. To reduce the T_f value, one can increase the damping ratio of the system or settling time as the constraints of our optimization problem.

We are now to investigate the effect of PWPFM parameter setting of a specified input angle, e.g., $J\Theta_{ref}/U_m$=50 deg.s^2, on the performance of the control system for other values of reference input angles. Fig. 17 shows the number of thruster firings versus quasi-normalized input angle when the PWPFM parameters are set for an input of 50 deg.s^2, compared to the optimum values obtained for each corresponding input. The dash-dotted line represents the results of applying the optimum setting corresponding to the input of 50 deg.s^2 to the whole input range, that clearly may not satisfy our optimization constraints. The solid line presents the optimum values corresponding to each input angle. Similarly, Fig. 18 compares the fuel consumption for the afore-mentioned cases. As we expected, our optimization constraints are violated in a small interval in Fig. 18, i.e., the values of the dash-dotted line lays below the optimum values of the solid line. According to Figures 17 and 18, to enhance the performance of the system, it is suggested that the optimum parameter setting be utilized for each input angle.

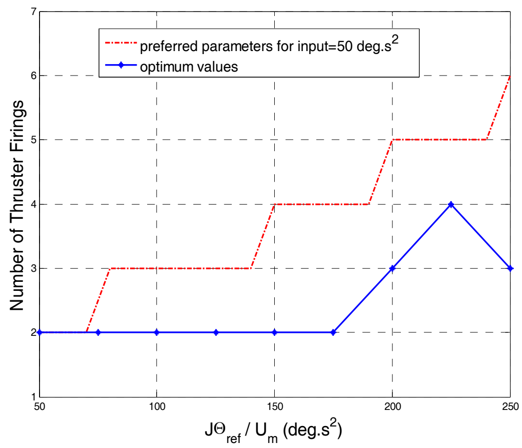

Figure 17. Comparison of optimum and non-optimum parameter setting in number of thruster firings

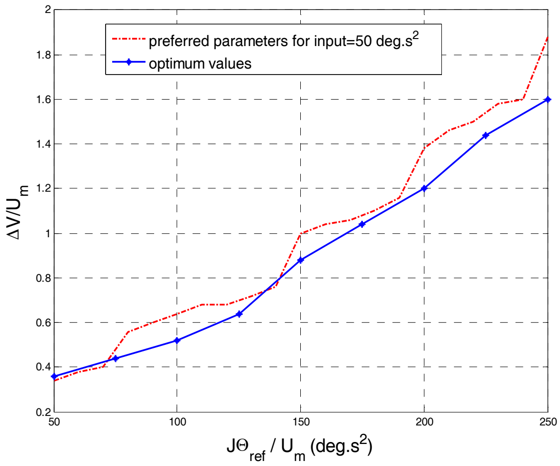

Figure 18. Comparison of optimum and non-optimum parameter setting in fuel consumption

Conclusions

The preliminary design of PWPFM parameters has been performed for quasi-normalized equations for a single-axis attitude control of rigid spacecraft in quasi-normalized form and the preferred regions of PWPFM parameters have been suggested. The main advantage of the method is to obtain the preferred values of grouped parameters, regardless of the value of each parameter separately. Besides, the number of parameters will be reduced, resulting in less computational burden. The preferred regions of parameters are optimized by grid search method for two performance indices, namely, thruster firings and fuel consumption. Because of the unmodeled dynamics and the simplification assumptions, the suggested regions of parameters have also been provided. Since the optimum values and the preferred regions depend on the value of the reference angle input, the suggested regions are presented for a range of input angles for rest-to-rest maneuvers. It should be noted that the present study is based on noise-free sensors assumption. The preferred region needs to be modified in the presence of noise for practical implementation.

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