Comparing Eqs. in our paper:

of normal force. Substituting can be simplified:

Under the conditions stated in Sec. 3.3 of our paper, this equation response to the shaped command will improve state error and less residual vibration.

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Dr. Shahruz is correct in asserting that exact cancellation of frictional terms is not possible. However, nowhere in our paper do we claim exact cancellation, nor does our method require exact cancellation of the friction effects. In fact, a large section of our paper is devoted to experimentally examining the effects of inaccuracies in the implementation of our technique. Therefore, we are alarmed that he has come to such a conclusion and that this journal would publish such an erroneous statement.

Our paper shows that partially canceling the friction effects will lead to an improvement in performance over standard input shaping techniques. More specifically, consider the system model given in our paper [1]:

\[ m\ddot{\chi} + (b + K_D)\dot{\chi} + K_P\chi = K_Pu - \text{sign}(\dot{\chi})\mu_kN \]  

(1)

Under the conditions stated in Sec. 3.3 of our paper, this equation can be simplified:

\[ m\ddot{\chi} + (b + K_D)\dot{\chi} + K_P\chi = K_Pu - \text{sign}(\dot{\chi})\mu_kN \]  

(2)

Equation (2) implies that friction can be viewed as a disturbance force with a constant magnitude. Standard input shapers are not designed to compensate for such disturbances. Therefore, if a standard input-shaped step command was used as the input \( u \), then the system would not settle at the desired final setpoint and there might be some residual vibration.

Now consider using the friction-compensated command \(^1\) given in our paper:

\[ u = \frac{\mu_kN}{K_P} \text{sign}(\dot{\chi}) + v \]  

(3)

where \( \mu_kN \) are estimates of the coefficient of kinetic friction and normal force. Substituting (3) into (2) yields

\[ m\ddot{\chi} + (b + K_D)\dot{\chi} + K_P\chi = K_Pu - \text{sign}(\dot{\chi})(\mu_kN - \mu_kN) \]  

(4)

Comparing Eqs. (2) and (4), it is clear that a reasonable estimate of \( \mu_kN \) will yield a reduction in the magnitude of the friction “disturbance” force. As the magnitude of the term decreases, the response to the shaped command will improve (smaller steady state error and less residual vibration). An exact cancellation of the last term in (4) is not necessary for this improved performance.

Contrary to the comments of Dr. Shahruz, this type of feedforward friction cancellation strategy is fairly common, although applying it to input shaping is a new idea. Many motion controllers on the marker, such as Siemens, Adept, Newport, Panasonics, etc., include analogous feedforward friction compensation with their PD and PID feedback control algorithms.

As for the issue of robustness, the great robustness properties of input shaping are well known and have appeared in hundreds of papers. We refer the reader to only a small fraction of these papers here [2–11]. This robustness is the primary reason input shaping is installed on literally millions of machines worldwide ranging from mainframe computers to small piezo actuators. In fact, input shaping can be made arbitrarily robust to modeling errors in natural frequency and damping ratio [10]. It is simply a question of trading off the robustness with the rise time. Unfortunately, a method for making the technique arbitrarily robust to errors in the kinetic coefficient of friction has not been developed. This is an admitted limitation of our approach. However, even with a poorly estimated coefficient, our technique will improve performance over standard input shaping. Furthermore, our control system contains a feedback controller that adds robustness in terms of final positioning accuracy and disturbance rejection.

The input shaping method proposed in our paper was not designed to be extremely robust to modeling errors. Our main focus was on compensating for the frictional effects, not generating highly robust commands. However, it is possible to combine our friction-compensation scheme with more robust input shaping approaches [11]. Robustness information for the technique under discussion was presented primarily in Figs. 14 and 15. These figures show the results from hundreds of experiments that were performed while varying the impulse amplitudes and times in the input shaper. This directly negates issue (2), item (iii) raised by Dr. Shahruz. In addition, because the impulse times are derived from the system frequency and the impulse amplitudes are derived from the system damping ratio and kinetic friction, these results also address issues (2), item (i) and (2), item (ii).

In conclusion: (1) our method does not require exact cancellation of the nonlinear friction term, and (2) the results from many experiments well document the robustness properties of our approach.

References


\(^1\)Note that Dr. Shahruz has confused our reference command signal with our control law. Our system is under PD feedback control.