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Biodynamic Feedthrough Compensation and Experimental Results Using a Backhoe

Heather C. Humphreys, Wayne J. Book and James D. Huggins
Mechanical Engineering Department, Georgia Institute of Technology

ABSTRACT

In some operator-controlled machines, motion of the controlled machine excites motion of the human operator, which is fed back into the control device, causing unwanted input and sometimes instability; this phenomenon is termed biodynamic feedthrough. In operation of backhoes and excavators, biodynamic feedthrough causes control performance degradation. This work utilizes a previously developed advanced backhoe user interface which uses coordinated position control with haptic feedback, using a SensAble Omni six degree-of-freedom haptic display device. Backhoe user interface designers and our own experiments indicate that biodynamic feedthrough produces undesirable oscillations in output with conventionally controlled backhoes and excavators, and it is even more of a problem with this advanced user interface. Results indicate that the coordinated control provides more intuitive operation, and the haptic feedback relays meaningful information back to the user. But the biodynamic feedthrough problem must be overcome in order for this improved interface to be applicable. For the purposes of reducing model complexity, the system is limited to a single degree of freedom, using fore-aft motion only. This paper investigates what types of controller-based methods of compensation for biodynamic feedthrough are most effective in backhoe operation, and how they can be implemented and tested with human operators.

INTRODUCTION

Biodynamic feedthrough occurs in operation of many types of vehicles and machines where the operator is a passenger. This phenomenon has been widely studied in the case of fighter pilots, but it is also seen in many other circumstances where it has not been extensively investigated. In some types of machines, the problem can be mitigated by simple means such as decoupling the axes of the input and output or adding vibration isolation to the cab. However, in cases where the operator controls more degrees of freedom and experiences larger accelerations, such as fighter jets or excavators/backhoes, these methods are often not sufficient. The unwanted input resulting from biodynamic feedthrough cannot be measured during operation, since it cannot be decoupled from the operator's desired command. This unwanted addition to the operator's command is highly correlated with the output and acts as a feedback loop.

This work is part of a larger group effort to improve operator interfaces for hydraulic machinery, in particular, backhoes and excavators. In an earlier project, a testbed was developed which uses a new, advanced, more intuitive operator interface. This testbed is called the Haptically Enhanced Robotic Excavator (HEnRE), shown in Figure 1. Tests indicated that this new interface has advantages of providing additional information to the operator in the form of haptic feedback, and it is much easier to learn, as compared with the conventional operator interface. However, operator studies showed that this new interface is more susceptible to biodynamic feedthrough. Biodynamic feedthrough is also a known problem in conventional backhoes and excavators.

Figure 1. Haptically Enhanced Robotic Excavator (HEnRE) Testbed

The main goals of this research are (1) to investigate and model the effect of biodynamic feedthrough on a backhoe control system, (2) to develop compensation to reduce the adverse effects of biodynamic feedthrough, and (3) to conduct testing with human subjects in the loop to determine the overall improvement to the system.

BACKGROUND

BIODYNAMIC FEEDTHROUGH – Despite the impact on heavy machinery operations, only a few publications on biodynamic feedthrough consider hydraulic equipment applications. In [1], an investigation on biodynamic feedthrough in excavator operation is performed using simplified mass-spring-damper models, though the experimental validation of the modeling is limited.

Under a contract for the US Air Force [2], [3], an in-depth study on biodynamic feedthrough was performed by Systems Technology, Inc. This study focused on the development of biomechanical models for the human pilot, to simulate the interaction between human body dynamics and structural modes in manual control systems. Unfortunately for researchers on heavy machinery, they assumed a pilot body position which makes the models invalid for the backhoe. Nonetheless, the data can be helpful in determining the overall effects of biodynamic feedthrough. In general, results indicate that the effects of biodynamic feedthrough are primarily of an involuntary nature, meaning that any cognitive or neuro-muscular compensation is negligible. Other investigations involving model-based cancellation for biodynamic feedthrough have been done based on experiments with a seated operator controlling a single degree-of-freedom platform; these investigations found human variability to be a significant problem ([4], [5]). Yet another device was patented which describes an actuated "biodynamic resistant control stick" developed for aircraft control, which actively varies the joystick's spring return force as a function of the aircraft motion [6].

More specific to this research, two publications present preliminary studies on biodynamic feedthrough in the HEnRE system. One paper presents a system model showing the effects of the biodynamic feedthrough with parameters specific to the HEnRE hardware. This includes models for each of the major dynamic components, including the human body [7]. The other paper presents simulation results for several controller-based approaches aiming to reduce cab acceleration [8].

VIBRATION COMPENSATION IN HYDRAULIC MACHINERY – Numerous publications over past decades involve active vibration control designs for minimization of cab motion in vehicles, yet this research has been done primarily for ergonomic purposes rather than performance. One recent simulation study investigated a sky-hook damping approach, using a linear quadratic regulator (LQR) optimal controller, with actuated suspension for vibration control of a quarter car model [9]. Rahmfeld and Ivantysynova presented a review paper that discusses various forms of passive, semi-active and active vibration control for mobile hydraulic equipment structures [10]. In [11], active cab motion reduction for a wheel loader is achieved using an LQR-based state feedback controller. The working implement has dual functionality, but it serves each purpose at different times during operation.

CONTROL OF BACKHOES AND EXCAVATORS – For several decades the industry standard in backhoe control has been the same 2-joystick, 4-DOF mapping currently in use, but recently several researchers have investigated the use of coordinated control to allow for more intuitive backhoe control. In the area of coordinated control, an advanced user interface for a backhoe has been developed at Georgia Tech, called the Haptically Enhanced Robotic Excavator (HEnRE), which uses coordinated position control along with haptic feedback. The HEnRE system is described in [12], [13], [14], [15] and [16].

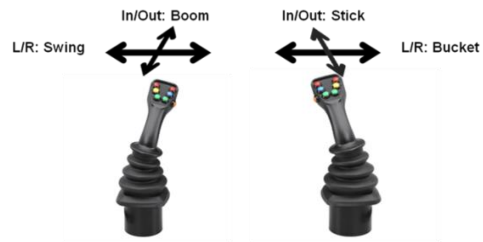

Figure 2. Conventional two joystick interface mapping

Figure 3. SensAble Omni 6-DOF haptic input device for coordinated control

This system uses the SensAble Omni™ six degree-of-freedom input device shown in Figure 3 for coordinated position control.

GOALS AND APPROACH

OVERALL RESEARCH PROJECT GOALS – Figure 4 represents the biodynamic feedthrough loop in backhoe valve/cylinder control. In general, the goal is to minimize the effects of signal *H(s)* on the system output.

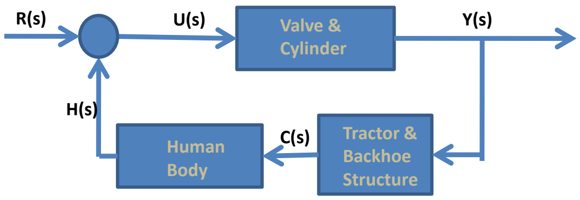

Figure 4. Biodynamic feedthrough feedback loop

The signal *R(s)* represents the operator's intended command input, *U(s)* represents the valve command, *Y(s)* represents the cylinder position output, *C(s)* represents cab motion, and *H(s)* represents the unwanted motion of the operator's hand resulting from the biodynamic feedthrough. The undesirable hand motion *H(s)* cannot be directly measured in operation, since it cannot be decoupled from the intended hand motion *R(s)*.

One approach to reducing the biodynamic feedthrough involves reducing the cab vibration so that the human is excited less. Reduction of cab motion can be achieved by several different methods, including filtering of the valve command signal, input shaping the command signal, or active vibration control using the backhoe arm itself. These methods are all investigated in this research. With the filtering approach, a notch filter is placed at each structural natural frequency, minimizing the excitation of those frequencies by the backhoe arm. Active vibration control using the working arm for vibration damping uses the cab acceleration measurement as feedback; as a result, it may compensate for some disturbances and nonlinear effects. However, it is a much more complex controller design and requires more extensive modeling; in addition, the backhoe arm has competing objectives of tracking the operator's command input and actively reducing cab acceleration. The main goal is to develop a new cylinder position feedback controller which reduces cab vibration excitation. It is desirable to compensate for cab vibration using the working implement itself, in order to minimize cost.

SPECIFIC RESEARCH QUESTIONS – The following questions are addressed in this research.

- Does biodynamic feedthrough degrade operator tracking performance?
- Can the applied compensators reduce cab vibration?
- Can the applied compensators improve operator performance?
- Every form of vibration compensation results in some form of control performance degradation (e.g. shakiness, slower response, etc.). How do the operators perceive the controller performance, and are these noticeable?

In human operator testing of manual control systems, researchers sometimes find that operator performance and the operators' perception of controller performance are different, especially in cases where a new user interface is replacing a conventional one.

TESTBED APPARATUS – The system uses a 4410 series John Deere tractor with a Model 47 backhoe that has been retrofitted with electro-hydraulic proportional directional valves, and uses the original constant displacement pump. A wide array of sensors, including position sensors for each cylinder and a 3-axis MEMS accelerometer mounted on the base of the tractor seat have been added for sensing the position and movements of the device to feedback into the overall system. In addition to these sensors, the HEnRE system uses a SensAble Omni™ commercial six degree-of-freedom (DOF) haptic display input device mounted beside the tractor seat. This device enables coordinated position-to-position mapping from the input to the backhoe arm. The backhoe controller uses software written using MATLAB/Simulink™ with xPC Target™ for real-time control implemented on a dedicated PC-104 target. A separate Windows host PC is used to control the SensAble Omni™. The two devices communicate via Ethernet with UDP protocol, and the target sample rate is set to 1000 Hz.

MAJOR ASSUMPTIONS AND SIMPLIFICATIONS – Biodynamic feedthrough presents a very complex problem in the control of high degree-of-freedom machines such as backhoes and excavators. As an initial step, in order to make the problem more manageable, some significant simplifications and assumptions were made.

The system is limited to a single degree-of-freedom, fore-aft motion with small displacements of the backhoe arm. This approximation is made possible by operating the backhoe only within a small angle approximation and in a configuration that produces primarily fore-aft motion of the backhoe arm, the cab, and the human body. Fore-aft motion of the human hand produces approximately fore-aft motion of the backhoe arm and structure, as illustrated in Figure 5.

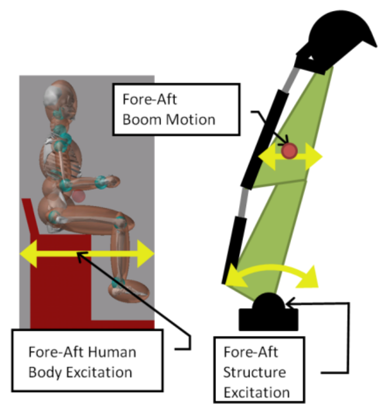

Figure 5. Single degree-of-freedom approximation

In addition, only one joint is actuated at a time, either the stick or the boom. The arm is limited to small motions in each case, which produce primarily fore-aft motion of the cab and human. For this testing, only the boom (shoulder) joint is actuated.

CONTROLLER DESIGNS

For coordinated position control, a feedback controller is required, regardless of whether or not vibration compensation is applied. In this research, two distinctly different forms of control algorithms are tested. The first is a PID-based controller, as shown in the block diagram in Figure 6. The second is a full state feedback controller with state feedback gain vector determined as a linear quadratic regulator (LQR), as shown in the block diagram in Figure 7. The controllers are tuned without vibration compensation. These two control algorithm types cannot be tuned to be equivalent, so the experiment has two distinct baselines. Then different forms of vibration compensation are added to each.

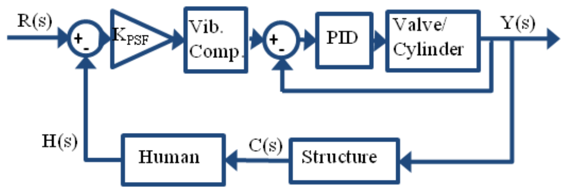

Figure 6. PID-based controllers with biodynamic feedthrough

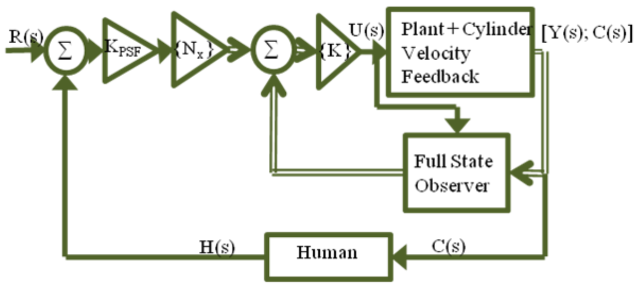

Figure 7. State feedback controllers with biodynamic feedthrough

Two forms of vibration compensation are added to the PID controller: (1) a notch filter placed at the structure natural frequency, and (2) an input shaper. Both forms of PID-based vibration compensation are passive. For the LQR state feedback controller, active damping is added using the cab acceleration measurement as feedback. A total of five controller treatments are tested in this research.

- PID controller, non-vibration-compensating
- PID controller with notch filter
- PID controller with input shaper
- LQR state feedback controller, non-vibration-compensating
- LQR state feedback controller with active vibration compensation

Addition of vibration compensation changes the system dynamics, somewhat detuning the controllers. All forms of vibration compensation degrade the cylinder tracking performance in different ways; some may cause it to be more sluggish, while others may feel less smooth. One goal is to show through human subject experiments that the reduction in biodynamic feedthrough outweighs any performance degradation resulting from vibration compensation.

VIBRATION COMPENSATION EXPERIMENTS

The goal of this first set of experiments is to test the controllers' performance in terms of cylinder tracking and cab motion reduction, neglecting biodynamic feedthrough. Two types of software inputs to the boom position controller were tested, an S-curve (integrated trapezoidal velocity profile) and a swept sine. The S-curve is a large amplitude, slowly varying signal, primarily intended to test position tracking performance; this signal is not aggressive and does not substantially excite cab motion. The swept sine is a smaller amplitude signal, ranging from 0-8 Hz; this signal excites considerable cab vibration and is intended to test cab vibration reduction performance. Results are shown in Table 1 and Table 2.

Table 1. Cylinder Tracking Mean Squared Errors [mm^2] for Software Input

Controller	*S-Curve Input*	*Swept Sine Input*
PID	4.84	4.57
PID + Notch Filter	7.72	2.75
PID + Input Shaper	14.63	2.62
LQR – No Vibration Compensation	15.26	3.08
LQR + Vibration Compensation	26.24	3.20

Table 2. Mean Squared Cab Acceleration [$(mm/s^2)^2$] (x10^5) for Software Input

Controller	*S-Curve Input*	*Swept Sine Input*
PID	0.65	6.98
PID + Notch Filter	0.56	1.17
PID + Input Shaper	0.52	0.23
LQR – No Vibration Compensation	0.48	2.52
LQR + Vibration Compensation	2.24	1.42

These results generally show that the vibration compensating controllers can substantially reduce cab vibration with the swept sine input. They also show that the vibration compensation tends to cause poorer tracking performance with the slowly varying S-curve signal.

HUMAN OPERATOR EXPERIMENT PROCEDURE

Ideally, the human operator experiments should mimic real-world backhoe operation as much as possible, in order to produce the most accurate results in terms of comparison between treatments. However, the single degree-of-freedom component of a dig cycle would not sufficiently excite the cab motion; therefore, a more aggressive input is used. In order to provide a reference that is independent of the unwanted input from biodynamic feedthrough, a tracking-pursuit experiment is used.

EXPERIMENT OVERVIEW – This experiment consists of a human operator tracking a desired command signal shown on a monitor, using the boom (shoulder) cylinder. This produces approximately in-out, or fore-aft, motion of the entire backhoe arm. In order to test the controllers without the effects of biodynamic feedthrough, two workstations were used, one with the operator on the tractor and one with the operator seated at a desk beside the tractor. With the operator off the tractor, the cab motion does not feed back into the input, and biodynamic feedthrough is eliminated. For each test subject, five compensators were tested (as described earlier) at each of the two workstations, for a total of ten test runs per subject. Figure 8 shows a picture of the on-tractor workstation, with the monitor mounted in front of the operator and the arm in the configuration used for testing.

Figure 8. Operator workstation on tractor with backhoe arm in experiment configuration

For this pilot study, a total of 8 participants were tested, recruited primarily from engineering graduate students. The order of presentation of controllers was randomized and undisclosed to the subjects; they were not aware of which type of controller they were testing. A survey was presented after each controller test.

TRACKING-PURSUIT EXPERIMENT – At each workstation, a monitor display shows two signals in real-time: the measured boom cylinder position and a software generated signal that the operator is instructed to track. Dig cycles tend to consist primarily of motions between a series of waypoints. Therefore, the tracking signal was designed to similarly be comprised of a series of steps. The steps occur at a cycle time of 2 seconds, and the heights are randomized by MATLAB's random number generator, then scaled and limited appropriately. The duration of each test is 140 seconds, for a total of 70 random steps for each treatment and operator. This number proved to be sufficient to obtain similar standard deviations across tracking signals, ensuring a fair comparison between treatments.

SURVEY – A survey was presented to each operator after each treatment. It requests that the operator rate each controller in terms of the following metrics:

- Overall controllability
- Accuracy
- Smoothness
- Speed of response

The ratings are on a scale from 0=very poor to 6=excellent. It also asks an open-ended question about what were their likes and/or dislikes about the controller treatment.

DATA COLLECTION – Two main data points are collected from the boom cylinder tracking experiment for each treatment and operator.

- Mean squared cylinder position tracking error
- Mean squared cab acceleration

From the surveys, the operators' ratings of each controller in terms of the four metrics provide four more data points.

HUMAN SUBJECT PILOT STUDY RESULTS

TRACKING EXPERIMENT – In general, the sample size for this pilot study was not sufficiently large to obtain statistical significance or a large effect size. However, there are some apparent trends. Table 3 shows the average mean squared cab accelerations from the human operator study. It indicates that the input shaper and active vibration compensation are able to reduce cab vibration with the operator in the loop.

Table 3. Mean Squared Cab Acceleration [$(mm/s^2)^2$] ($\times 10^5$)

Controller	*Operator On Tractor*	*Operator Off Tractor*
PID	4.08	3.02
PID + Notch Filter	4.35	2.43
PID + Input Shaper	3.55	2.48
LQR – No Vibration Compensation	10.25	4.32
LQR + Vibration Compensation	8.96	4.18

Figure 9 shows box plots for the mean squared cylinder tracking with the operator on the tractor. The boxes show the 25th-75th percentiles, and the red lines show the medians. These show fairly large variance, particularly for the active compensation.

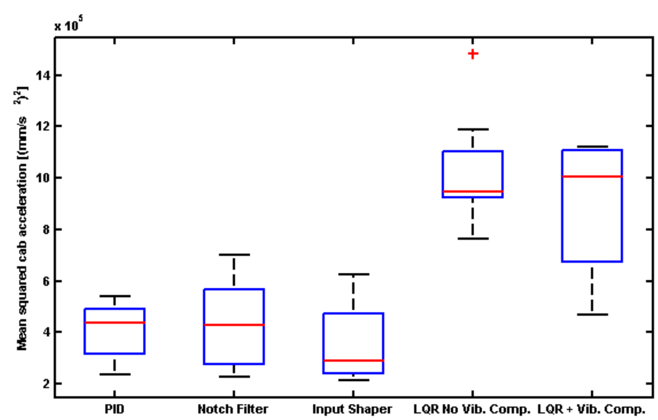

Figure 9. Box plots for mean squared cab acceleration, operator on tractor

The cab acceleration measurements indicate that the controllers can reduce cab vibration. From Table 4, the results for the operator on the tractor do show a slight but not statistically significant improvement with the input shaper and active vibration compensation; however, as in the case of the vibration reduction, the notch filter tends to degrade performance with the operator on the tractor.

Table 4. Cylinder Tracking Mean Squared Errors [mm^2]

Controller	*Operator On Tractor*	*Operator Off Tractor*
PID	152.6	120.4
PID + Notch Filter	188.3	108.6
PID + Input Shaper	143.9	115.7
LQR – No Vibration Compensation	234.8	91.6
LQR + Vibration Compensation	200.1	114.4

Figure 10 shows box plots for mean squared cylinder tracking, with the operator on the tractor. The variances are large with this small sample set; these may result in part from learning effects over the course of the test. Also, some operators were more experienced with this type of machine control than others. Increased practice time may help to decrease the variance.

OPERATOR SURVEY – Again, it is important to note that the sample size for this pilot study is smaller than what would be needed to obtain statistical significance. The operator survey showed some interesting results. First, when seated *on the tractor,* operators generally rated the input shaped PID controller higher than the non-vibration-compensated PID, and they rated the LQR controller with active compensation higher than the LQR without vibration compensation, in all four categories. Figure 11 shows the average operator ratings of each controller when seated on the tractor.

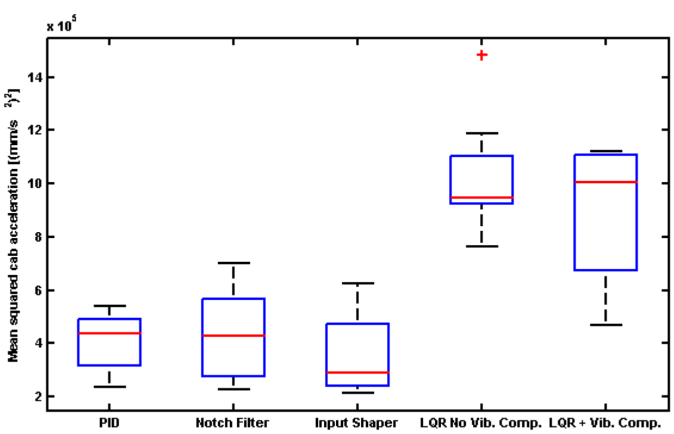

Figure 10. Box plots for mean squared cylinder tracking, operator on tractor

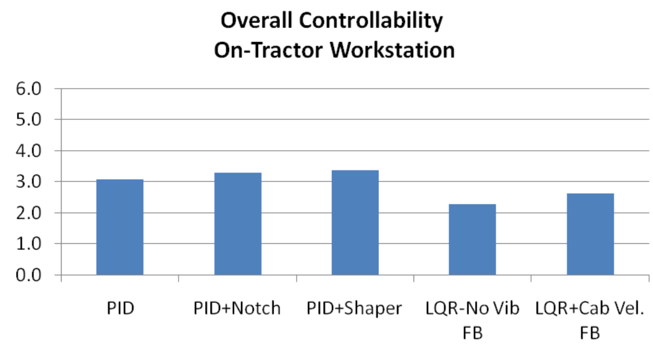

Figure 11. Mean operator ratings in terms of overall controllability, on-tractor workstation

When using the off-tractor workstation, operators most strongly preferred the LQR without vibration compensation; for the on-tractor workstation, this controller is rated lowest.

CONCLUSIONS AND FUTURE WORK

This work presents experiment setup and results from a pilot study for ongoing human subject tests on potential controller-based treatments for biodynamic feedthrough in backhoe operation. While results are generally not statistically significant with this small sample set, they do indicate some improvement both in terms of reduction in cab vibration and reduction in cylinder tracking error. The next step is to run a second set of human operator experiments with a larger number of subjects. Once those results are obtained, further statistical analyses will be performed to determine statistical significance and effect size of the results.

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