

MODELING OF BIODYNAMIC FEEDTHROUGH IN BACKHOE OPERATION

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ABSTRACT

An advanced backhoe user interface has been developed which uses coordinated control with haptic feedback. Results indicate that the coordinated control provides more intuitive operation that is easy to learn, and the haptic feedback also relays meaningful information back to the user in the form of force signals from digging forces and system limitations. However, results show that the current system has significant problems with biodynamic feedthrough, where the motion of the controlled device excites motion of the operator, resulting in undesirable forces applied to the input device and control performance degradation. This unwanted input is difficult to decouple from the intentional operator input in experiments. This research presents an investigation on the effects of biodynamic feedthrough on this particular backhoe control system, using system identification to empirically define models to represent each component. These models are used for a preliminary simulation study on potential methods for biodynamic feedthrough compensation.

INTRODUCTION

A variety of user interface methods have been developed for backhoes and excavators, most of which have significant problems with biodynamic feedthrough. The backhoe user interface used in this study has significant advantages over state-of-the-art interfaces, specifically in the areas of intuitiveness and haptic feedback; however, the oscillations resulting from biodynamic feedthrough make this system very difficult to control. The main goals of this study are to develop models for this system, to understand the mechanisms by which biodynamic feedthrough affects the system, to use those models to test

the effectiveness of potential compensation methods, and to develop and apply effective compensation. This paper presents the first step, which is development of a full system model to represent the dynamics of this system, including the human body dynamics. It also presents simulation results for a few simple potential methods for biodynamic feedthrough compensation.

An advanced user interface for a backhoe has been developed, called the Haptically Enhanced Robotic Excavator (HENRE), which uses coordinated position control with haptic feedback. The HENRE system is described in [1], [2] and [3], and it is pictured in Figure 1.

The HENRE system uses a SensAble Omni™ commercial six degree-of-freedom (DOF) haptic display input device, shown in Figure 2. The Omni is mounted beside the tractor seat, in a manner similar to state-of-the-art electronic joysticks. It enables coordinated position-to-position mapping from the input device to the backhoe arm, allowing the use of a computer for the inverse kinematics calculations. In contrast, state-of-the-art backhoe user interfaces use position-to-velocity mapping with two



FIGURE 1. HAPTICALLY ENHANCED ROBOTIC EXCAVATOR (HENRE)



FIGURE 2. SENSABLE OMNI™ [SENSABLE.COM]

separate 2-DOF joysticks (totaling 4-DOF) to provide four independent inputs to control four actuators on the backhoe arm. The HEnRE interface provides much more intuitive operation.

The backhoe controller uses software written using MATLAB/Simulink™ with xPC Target™ for real-time control, as well as C++. Many systems using coordinated position control of backhoes and excavators have been developed. The HEnRE system has the economic advantage that it utilizes proportional valves and a constant displacement pump, rather than servo valves and variable displacement pumps, which tend to be cost-prohibitive; methods for efficient control of the pump for this system are discussed in [4]. Methods for providing haptic feedback to represent load forces and system limitations are discussed in [5].

Biodynamic feedthrough is a widely recognized problem in the area of high-performance aircraft, and it has been an area of research in the aerospace industry for several decades. It is also significant in control of mobile hydraulic equipment, though it has received less attention in this area. Backhoe user interface designers claim that the new electronic joysticks have more problems with biodynamic feedthrough than the earlier manual joysticks. Both versions of joysticks are used as rate-controllers. The earlier manual joysticks tend to have larger workspace sizes and more damping; these characteristics make the earlier manual joysticks less susceptible to biodynamic feedthrough. The HEnRE system uses position control.

Only a few publications on biodynamic feedthrough consider hydraulic equipment applications. In [6], a similar investigation on biodynamic feedthrough in excavator operation is performed using simplified mass-spring-damper models, though the experimental validation of the modeling is limited. Another similar simulation-only investigation is presented in [7].

An in-depth study on biodynamic feedthrough was performed by Systems Technology, Inc., under a contract for the US Air Force [8-9]. It focuses on development of lumped-parameter biomechanical models for the human pilot, for the purpose of developing software to simulate the interaction between human body dynamics and structural modes in manual control systems. The publications do not present detailed human body models for fore-aft motion. In general, results indicate that biodynamic feedthrough effects are primarily of involuntary nature;

any cognitive or neuro-muscular compensation is negligible. They also note that it is the difference between the human body motion and cockpit motion that results in unwanted input; measures taken to isolate the pilot or input device from cockpit vibration would likely aggravate the biodynamic feedthrough effects. Another study, discussed in [10], presents a model of the human pilot's arm for lateral motion only.

Two other investigations involve development of model-based cancellation compensation for biodynamic feedthrough, based on experiments with a seated operator controlling a single degree-of-freedom moveable platform. The first addresses the uncertainty in the human operator's dynamics by developing a different model for each operator [11]. The second addresses model uncertainties by developing a mu-synthesis based controller [12].

This research presents an investigation and model for the effects of biodynamic feedthrough in the operation of a backhoe system. Models are defined by system identification, which are validated by experiments. The first section gives an overview of the system model and its components. The next section gives a detailed description of the system identification, and the last section gives some preliminary simulation results.

SYSTEM MODELING OVERVIEW

The biodynamic feedthrough system is divided into four main components, which are modeled separately. The system is shown in Figure 3.

For model simplification purposes, only fore-aft motion is considered throughout the system. While the full HEnRE control system uses coordinated position control, this testing incorporates closed loop position control of only the stick (forearm) joint.

By appropriately positioning the backhoe arm and assuming small angle approximations, it can be assumed

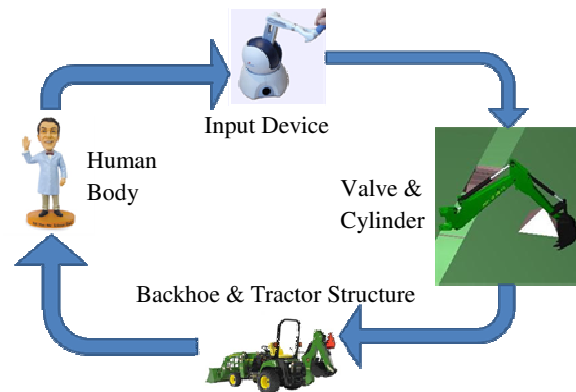


FIGURE 3. BIODYNAMIC FEEDTHROUGH SYSTEM COMPONENTS [JOHNDEERE.COM AND SENSABLE.COM]

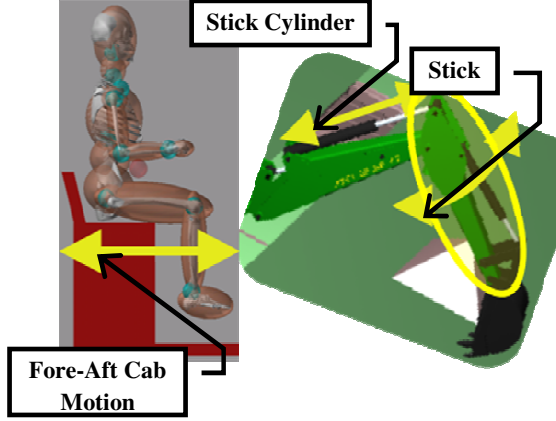


FIGURE 4. FORE-AFT MOTION EXCITATION, USING POSITION CONTROL OF STICK CYLINDER WITH SMALL ANGLE APPROXIMATION

that the backhoe stick motion provides solely fore-aft excitation, as described in Figure 4.

Transfer function models are created for each component. For the purposes of providing realistic haptic feedback, the SensAble Omni is designed with very low inertia and little mechanical damping. Therefore, the inherent dynamics of the Omni mechanical system are neglected in this modeling. The force generating capability of the Omni can be used to modify its dynamics as needed to improve the performance of the system.

The human body is modeled as transmissibility from seat motion to hand motion, with the body seated in a typical operating position. The tractor structure is similarly modeled as a mass-spring-damper system, with a transfer function corresponding to transmissibility from backhoe motion to seat motion.

Figure 5 shows a block diagram of the system, incorporating these transfer functions. The inner loop represents the cylinder position control loop, and the outer loop represents the biodynamic feedthrough loop. An appropriate transfer function is also included to simulate the valve/cylinder dynamics. A closed loop with PI controller is used to achieve position-to-position mapping from Omni motion to cylinder motion.

The reference input (u) represents the operator's desired command, the inner loop error signal (e) represents

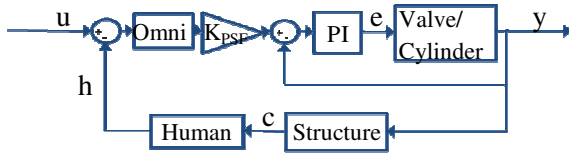


FIGURE 5. BLOCK DIAGRAM FOR BACKHOE STICK POSITION CONTROL SYSTEM WITH BIODYNAMIC FEEDTHROUGH

the valve command, the output (y) is the cylinder position, and signals (h) and (c) represent the motion of the human hand and cab, respectively. The position scale factor (K_{PSF}) corresponds to the ratio of the workspace limits for the Omni and cylinder.

SYSTEM IDENTIFICATION

System identification by spectral analysis was performed on three main components of the system: the valve/cylinder system, the backhoe/tractor structure, and the human body. Models for the backhoe system are developed based on first principles in [1-2]; however, in order to decrease model complexity and obtain a better match with measured data, models used in this work are primarily empirically determined. Motion of the backhoe stick joint was used as excitation, from an external software input signal in the form of a chirp sine; from this excitation, measurements of cab acceleration and operator's hand motion are obtained. The following measurements are used for model development: (1) hand position relative to cab position, obtained from using the Omni, equipped with encoders, used as a measurement device rather than an input device, (2) cylinder position, measured using a Balluff model BTL-E micropulse style linear position sensor, and (3) cab motion, measured using Analog Devices model ADXL330 3-axis MEMS accelerometers located at the operator's seat and at the Omni base.

The transfer functions are determined based on spectral analysis. Bode plots and coherence plots are computed based on measured data, and frequency domain curve fits are used to determine transfer functions to match the measured data. Measurement data are often noisy and some have low input-to-output coherence, especially those using accelerometer measurements. Filtering and large data sets are used in order to mitigate these issues as much as possible, typically 20-50 data sets, each 25 seconds long with 1000 Hz sample rate. The measurement data sets are converted using Fourier transforms, then Eqn. 1 and Eqn 2 are used to obtain the magnitude, phase and coherence relations between the input and output.

$$\hat{H}(f) = \frac{\hat{G}_{xy}(f)}{\hat{G}_{xx}(f)} \quad (1)$$

$$\gamma_{xy}^2(f) = \frac{\hat{G}_{xy}(f)^2}{\hat{G}_{xx}(f)\hat{G}_{yy}(f)} \quad (2)$$

where $\hat{G}_{xy}(f)$ is the crosscorrelation between input and output, $\hat{G}_{xx}(f)$ and $\hat{G}_{yy}(f)$ are autocorrelations for the input and output, respectively, and $\gamma_{xy}(f)$ is the cohe-

rence. The magnitude and phase of $\hat{H}(f)$ provide the Bode plots.

Valve/Cylinder

A transfer function from input signal to flow rate is developed empirically for this particular valve in [2], which forms a basis for the development of the model for the valve/cylinder. It gives a third order transfer function from input valve signal to output flow rate. For this testing, the input valve signal corresponds approximately to a velocity, and the output cylinder position is measured, indicating that the desired transfer function from input valve signal to output cylinder position should be approximately fourth order with a free integrator. The integration effect coupled with the difference in rod side pressure and cap side pressure cause significant drift in open loop control; therefore, the data for system identification are obtained from within the closed position-position control loop. A chirp sine signal is used as input to the closed loop with PI controller. The valve control signal, corresponding to the error signal inside the closed loop, is used as the input signal for system identification. The cylinder position measurement is the output. Figure 6 shows a

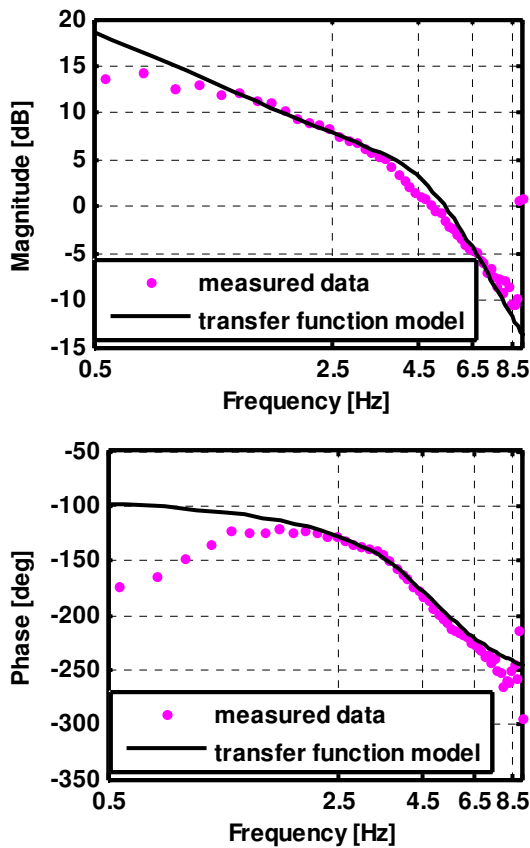


FIGURE 6. BODE PLOT FOR VALVE/CYLINDER MODEL AND MEASURED DATA

Bode plot comparing the valve/cylinder model and measured data.

The empirically determined transfer function for the valve/cylinder component is given in Eqn. 3,

$$\frac{Y(s)}{E(s)} = \frac{K_{VC} p_{1VC}}{s(s + p_{1VC})} \cdot \frac{\omega_{nVC}^2}{(s^2 + 2\zeta_{VC} \omega_{nVC} s + \omega_{nVC}^2)} \quad (3)$$

with poles $\omega_{nVC} = 5$ Hz and $p_{1VC} = 314$, gain $K_{VC} = 36$, and damping ratio $\zeta_{VC} = 0.45$.

Backhoes have inherently low bandwidth; high frequency components of the signals are not transmitted to the output. This model matches well with measured data in the upper frequency range of interest, but the coherence begins to decrease below ~ 1 Hz. This nonlinear relation at low frequencies may result from the combination of the deadband and measurement of the input within the closed loop; at low frequencies, the error is small and likely to remain within the valve deadband. This unmodeled nonlinearity is insignificant in the analysis of biodynamic feedthrough; as will be shown later, the biodynamic feedthrough has no significant effect at the low frequencies.

Structural dynamics of the tractor and backhoe

A similar system identification analysis was performed on the tractor/backhoe structural dynamics. For backhoes and excavators in operation, these dynamics vary depending on the soil properties, the use of outriggers and front-end loaders for stability, and other external factors. They also vary significantly from one system to another. It is important to note that this analysis is based on the current form of the HENRE system, with the tractor mounted on steel stilts for convenience in testing, rather than sitting on its wheels. The stilts setup is most likely stiffer than the system sitting on wheels. Therefore, the cab acceleration generated from this setup is most likely lower amplitude and higher frequency than that of a more standard tractor placement. Acceleration was measured at the base of the Omni and at the operator's seat. The measurements at both locations were very similar, indicating that the cab motion can be treated as a rigid body.

The transfer function for the structure is based on a series 2-mass-spring-damper system plus a gain, with two additional derivative terms to account for input position and output acceleration. This gives an equation of the form

$$\frac{C(s)}{Y(s)} = \frac{K_s s^2 (2\zeta_{s1} \omega_{sn1} s + \omega_{sn1}^2)}{(s^2 + 2\zeta_{s1} \omega_{sn1} s + \omega_{sn1}^2)} \cdot \frac{(2\zeta_{s2} \omega_{sn2} s + \omega_{sn2}^2)}{(s^2 + 2\zeta_{s2} \omega_{sn2} s + \omega_{sn2}^2)} \quad (4)$$

with damping terms $\zeta_{s1} = 0.126$ and $\zeta_{s2} = 0.223$, natural frequencies $\omega_{sn1} = 6.3$ Hz and $\omega_{sn2} = 6.5$ Hz, and gain $K_s = 200$.

These measurements have high coherence only in a small frequency range, near the natural frequencies of the structure. This structure has a large peak near 6 Hz; the amplitudes of the measured acceleration at considerably lower or higher frequencies are small, indicating that a small signal-to-noise ratio in these ranges is a likely contributor.

Simulation results show that biodynamic feedthrough occurs primarily in the frequency range near the natural frequencies of the structure; the smaller amplitude vibrations at lower and higher frequencies are less significant.

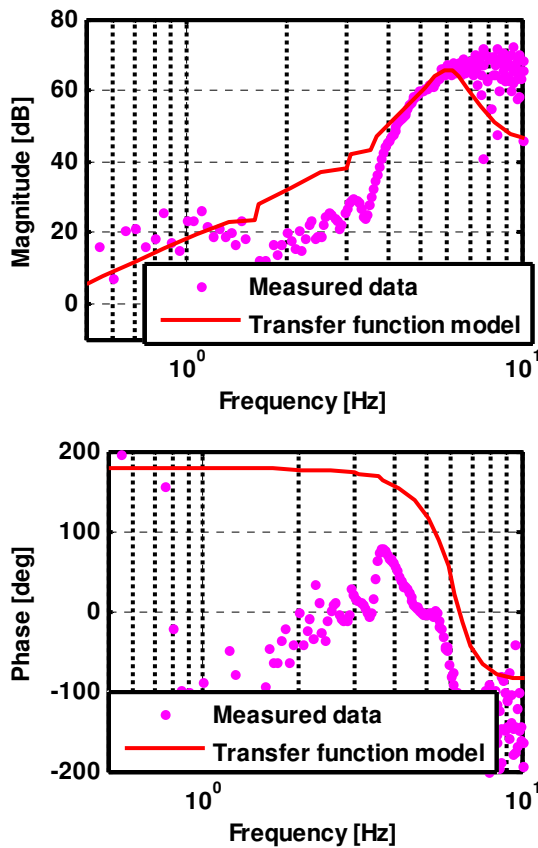


FIGURE 7. BODE PLOT FOR STRUCTURAL DYNAMICS – MEASURED DATA AND TRANSFER FUNCTION

Human body dynamics

A linear transfer function model is developed to represent the human body dynamics using similar methods. In this study, only nominal values for human body spring and damping parameters are considered; these parameters are expected to vary widely, and that parameter variation is a topic for future work. For the human model, data are obtained by two methods: 1) human subject trials, and 2) human body dynamic simulations using MSC.Adams™ and the add-on package LifeMOD™.

One difficulty in modeling biodynamic feedthrough is that the unwanted input resulting from the biodynamic feedthrough cannot be decoupled from the desired input. Most commonly in the literature, as in this study, the unwanted input is approximated in a separate set of experiments. The system is excited by the backhoe stick motion, the same as for the other component measurements. The stick motion is commanded from an external software input, and the Omni input device is used for measurement rather than command. Human operators in position for operation are instructed to hold the Omni as though operating the backhoe. This measures the Omni handle position with respect to the cab, giving a direct measurement of the unwanted Omni input as a function of backhoe motion. It should be noted that the original excitation signal is passed through the valve, cylinder and structure before exciting the human body; therefore, the input excitation to the human body has significant variations in signal power and signal-to-noise ratio across the range of frequencies.

LifeMOD™ software is also used to model the vibration response of the human body, which provides more consistent results than human subject trials. LifeMOD™ is an add-on to the dynamics simulator MSC.Adams™. This software allows the user to input body parameters such as overall height and weight, joint parameters, etc. Based on those inputs, it generates a set of 16 linkages and 18 joints with appropriately scaled masses, centers of mass, lengths, etc., to represent the human body, or the user can select median male or female parameters. Interactions with other bodies modeled in MSC.Adams can

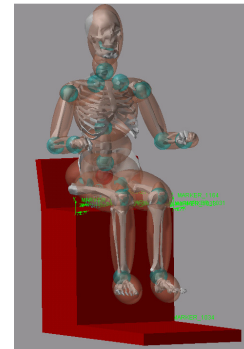


FIGURE 8. LIFEMOD/MSC.ADAMS MODEL OF HUMAN OPERATOR AND BACKHOE SEAT – SCALED FOR FEMALE TEST SUBJECT

also be included. The user can input individual joint stiffnesses and damping coefficients, or use the values from the standard Hybrid III crash dummy, with a scale factor. Figure 8 shows an image of a human operator on the backhoe seat, scaled to match the female test subject, used for correlating the LifeMOD simulation and human subject testing. The body is positioned such that the hand is placed at the nominal location of the Omni handle in the cab. A swept sine input is applied to the seat in the fore-aft direction, and the response at the hand is recorded.

Parameters for stiffness and damping of human body joints are variable and not well-known. In addition to variations from person to person, these values can vary significantly depending on joint angles and positions; in literature, these variations are sometimes modeled as ellipsoids, as discussed in [13]. They also vary depending on the activity level of the joint, as discussed in [14]; Jex and Magdaleno note a similar difference in biodynamic feedthrough depending on whether the operator is active or passive [8]. A number of research studies have investigated human body spring and damping parameters in various conditions, and results often vary by as much as an order of magnitude. Extensive testing on human body parameters is performed in the development and testing of the Hybrid III Crash Dummy [15]; these standard values, with a scale factor of 0.6 to account for a difference in activity level, are used in this analysis. This scale factor is determined based on values from similar sample LifeMOD™ simulations and by adjusting to match the frequency response of human test subject data. A comparison of magnitudes for input seat acceleration and output hand motion for two human test subjects, the median male LifeMOD model, and the transfer function model is

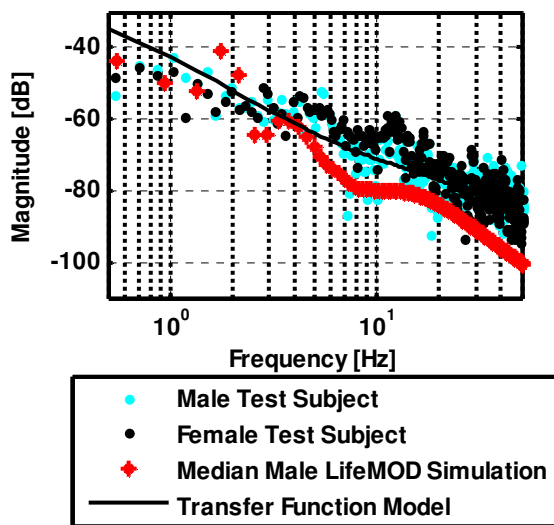


FIGURE 9. MAGNITUDE COMPARISONS FOR HUMAN MODEL

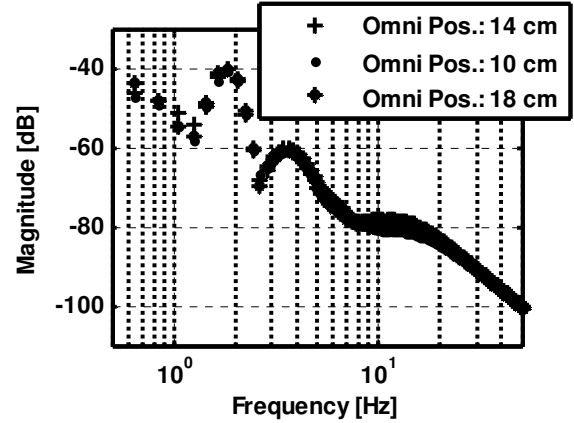


FIGURE 10. MAGNITUDE COMPARISONS FOR VARYING OMNI POSITION IN FORE-AFT DIRECTION WITH LIFEMOD™ MEDIAN MALE SIMULATION

shown in Figure 9.

The input signal for the human test subjects is an accelerometer measurement, which includes considerable noise, especially from motion induced by the running tractor motor. The transfer function model for the human body dynamics, with input seat acceleration and output hand motion, is given in Eqn. 5. The output hand motion is defined with respect to seat motion, not as an absolute position.

$$\frac{H(s)}{C(s)} = \frac{K_H (s + z_{1H})^2}{s^2 (s + p_{1H})^2} \quad (5)$$

with real zeros $z_{1H} = 50.3$, real poles $p_{1H} = 1.57$, and gain $K_H = 5$.

Tests are performed to investigate the effect of varying the Omni position on biodynamic feedthrough. The same tests as described previously are performed with the Omni in three different positions, a nominal position, four inches forward from nominal, and four inches back from nominal, using one human test subject and the median male LifeMOD model. The results from the LifeMOD simulation are shown in Figure 10. Position is varied only along the fore-aft axis.

These results, as well as the human test subject results, indicate that variation in Omni position with respect to the human body has little effect on vibration transmission into the input device.

SIMULATION RESULTS

These transfer functions were assembled into a complete system in MATLAB and Simulink, and the model stability and performance were investigated. Using

the nominal empirically derived values, the closed-loop full system transfer function has two unstable poles. The output cylinder position response to an input swept sine was simulated with and without biodynamic feedthrough. The input represents the intended hand motion. For the simulation with biodynamic feedthrough included, the block diagram is the same as in Figure 5. The system was simulated without biodynamic feedthrough by removing the outer feedback loop, which includes the human and structure transfer functions. The results are shown in Figure 11.

The current HEnRE hardware system does not appear to be unstable with biodynamic feedthrough; however, it is very difficult to control and does exhibit substantial oscillations, which appear to result from limit cycles. Limit cycles do not occur in linear models. However, it is expected that modifications which reduce the undesirable effects of biodynamic feedthrough in the linear system models, including simple parameter variations such as increasing the workspace size and damping of the input device, will have similar effects if applied to the hardware system. However, in the hardware, variability in the human operator and the structure must be taken into account.

The nominal position scale factor, shown as K_{PSF} in the system block diagram Figure 5, is defined as the ratio of the workspace size in the fore-aft direction of the input device to the travel distance of the cylinder. The nominal value for $K_{PSF} = 0.1097$, corresponding to an Omni fore-aft axis workspace size of 71 mm. If the Omni workspace size is doubled, corresponding to reducing K_{PSF} by half, then the system model is stable; cylinder position output for the same swept sine input with $K_{PSF}=0.055$ is shown in Figure 12.

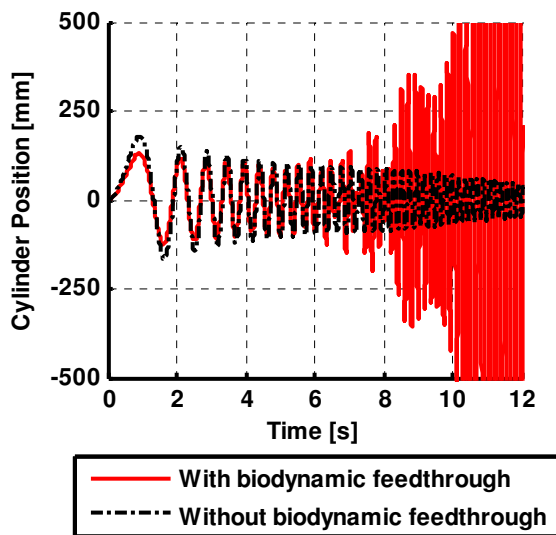


FIGURE 11. UNSTABLE TIME RESPONSE WITH BIODYNAMIC FEEDTHROUGH

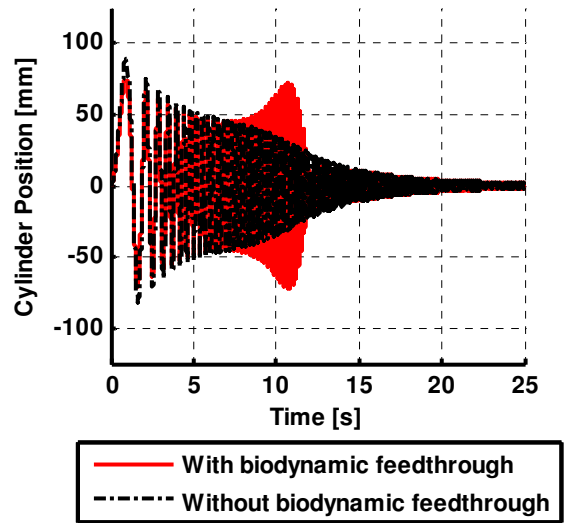


FIGURE 12. STABLE RESPONSE WITH BIODYNAMIC FEEDTHROUGH – OMNI WORKSPACE SIZE DOUBLED

A parameter study is performed on the position scale factor, for values corresponding to increases in the Omni workspace size by factors of 2 to 10, corresponding to a range of input device workspace dimensions of 142 mm to 711 mm. Figure 13 shows the ratio of the simulated cylinder position outputs with biodynamic feedthrough to the simulated cylinder position without biodynamic feedthrough, versus frequency.

This parameter study shows that for the linear system model, the effects of biodynamic feedthrough can be reduced and the system can be stabilized by increasing

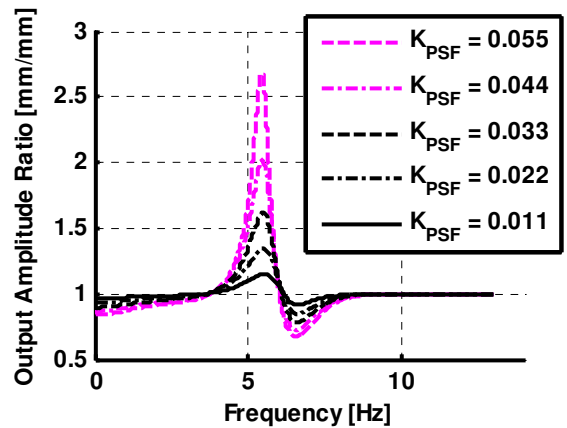


FIGURE 13. INPUT DEVICE WORKSPACE SIZE PARAMETER STUDY - RATIO OF SIMULATED OUTPUT WITH VS. WITHOUT BIODYNAMIC FEEDTHROUGH

the size of the input device workspace. The linear model is stable for all of the cases shown in Figure 13. However, ergonomic factors limit increases on this workspace size. These limitations are a topic for future work.

CONCLUSIONS AND FUTURE WORK

This paper presents a system model that can be used to evaluate potential compensation methods for biodynamic feedthrough. It also presents preliminary results for one simple parameter variation that could be used for compensation; however, these results must be validated by experiments. Many methods have been proposed for biodynamic feedthrough compensation, including active noise cancellation, adaptive filtering, and model-based cancellation, as well as some mechanical forms of vibration isolation and damping. Some have proposed using the force display capability of the input device to implement such compensation, in addition to haptic force reflection. Some of these methods may be evaluated using these models. Robustness to expected parameter variations, especially in the human body parameters, is crucial to any compensation method design.

Alternative input devices are also a topic for future work. While the SensAble Omni has an effective software interface, its mechanical design is not ideal for backhoe control. More robust haptic display devices with larger workspaces may be considered, as well as the use of coordinated resolved rate control using electronic joysticks.

ACKNOWLEDGMENT

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