Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Relating biodynamic feedthrough to neuromuscular admittance

Joost Venrooij, Mark Mulder, Marinus M. van Paassen, Max Mulder
Department of Aerospace Engineering
Delft University of Technology
Delft, The Netherlands
j.venrooij@student.tudelft.nl, mark.mulder@tudelft.nl, m.m.vanpaassen@tudelft.nl, m.mulder@tudelft.nl

David A. Abbink
Department of Mechanical Engineering
Delft University of Technology
Delft, the Netherlands
d.a.abbink@tudelft.nl

***Abstract*—When an operator in a moving vehicle is performing a manual control task, the accelerations to which the operator is subjected can result in unintentional control inputs. This biodynamic feedthrough (BDFT) depends on the properties of the control device and of the control limb. Humans can adjust the dynamics properties of their limbs, effectively changing the limb admittance. Previous studies of BDFT did not consider the effect of this adjustment. This paper describes a model for BDFT and an experiment in a moving base simulator with subjects performing a control task with a side stick. During the experiment the neuromuscular admittance was varied by using different control tasks, each requiring a different neuromuscular setting. The non-parametric results of this experiment show that the level of feedthrough is strongly dependent on both the frequency of the disturbance and the neuromuscular admittance. The results furthermore suggest that a relationship can be established between admittance and biodynamic feedthrough.**

***Keywords*—Biodynamic feedthrough, neuromuscular admittance, manual control, neuromuscular adaptation**

I. Introduction

The presence of accelerations during manual control tasks can degrade human control performance through various mechanisms [1][2]. One of these mechanisms is biodynamic feedthrough (BDFT), which refers to a process where accelerations cause involuntary limb motions. When coupled to a control device, these limb motions can result in unintentional control inputs.

BDFT can form a threat to safe operation of many types of manually controlled vehicles and devices, and therefore it is highly relevant to understand its mechanisms. An example of BDFT is the uncomfortable fore and aft motion of powered wheelchairs, known as 'bucking' [3]. BDFT is also considered a threat to safe operation of heavy hydraulic machines, such as excavators and bulldozers [4][5], high-speed aircraft in turbulence and vehicles over rough terrain (e.g. tanks and boats). Furthermore, BDFT has been recognized as the cause of phenomena like roll-ratchet [6][7].

This paper investigates the relation between BDFT and neuromuscular admittance. The neuromuscular admittance describes the dynamics of a limb that is in contact with the control device, by providing the dynamic relation between a force input and a position output. Neuromuscular admittance is highly adaptive and dependent on factors such as intrinsic and reflexive feedback, the level of muscle co-contraction and task instruction. In previous studies of BDFT, no attempt was made to measure neuromuscular admittance in relation to BDFT. Here, it is investigated how adaptation of the neuromuscular admittance influences BDFT.

First, in section II, a typical biodynamic feedthrough system is broken down in its main elements. Then, a model capable of describing the occurrence of biodynamic feedthrough is proposed in section III. To validate and parameterize the model, an experiment was conducted, described in section IV. The results of this experiment are presented and discussed in sections V and VI. Finally, the conclusions are presented in section VII.

II. Biodynamic Feedthrough Systems

A. Elements in biodynamic feedthrough systems

Figure 1 shows a schematic representation of a typical biodynamic feedthrough system. In this representation four main elements can be identified. The human operator (HO) acts as a controller in a manual control task. The HO is controlling the (partial) state of a controlled element (CE) by comparing the current state with a certain goal state. The HO can influence the state of the CE by means of a control device (CD). The CE can be subject to a disturbance signal that perturbs the state of the CE, for which the HO needs to compensate. The forces F_{dist} that work on the CD are force disturbances, perturbing the control device. The HO is connected to a platform (PLF), which is a moving, physical object, typically a vehicle. The accelerations of the PLF are called the motion disturbances M_{dist}. Biodynamic feedthrough occurs when the motion disturbances induce unintentional motion in the limb that is in contact with the CD, thereby leading to unintentional control inputs.

The feedthrough of PLF accelerations, via the body of the HO into the CD, is governed by two interfaces, one between the PLF and the HO and one between the HO and the CD, indicated by dashed boxes in Figure 1. An interface describes the properties of the mechanical connection that exists between two elements. The interface I_{PLFHO} describes the connection between the PLF and the HO. Typically, the

978-1-4244-2794-9/09/$25.00 ©2009 IEEE

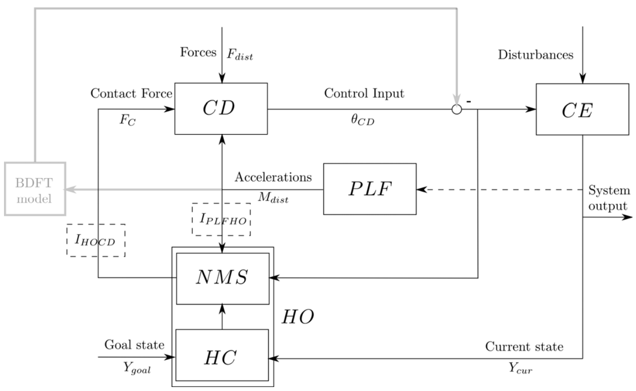

Figure 1. Elementary biodynamic feedthrough model, showing the elements of a BDFT system. HO is the human operator, who controls the controlled element (CE) with a control device (CD) by activation of the neuromuscular system (NMS). Platform (PLF) motion influences the motion of the NMS of the HO, which is coupled to the CD, yielding unintentional control inputs. The grey elements present the control signal cancellation method; the BDFT model provides an estimation of the the unwanted control inputs induced by PLF accelerations, which are subsequently substracted from the control input

HO is connected to the PLF by means of a seat and seat belts. The interface I_{HOCD} describes how the HO is manipulating the CD. One of the parameters that characterize this connection is the grip force. Restraints such as arm rests are also part of this interface.

In order to investigate the relationship between BDFT and neuromuscular admittance the content of the HO block in Figure 1 is further examined. The human operator can be split in the neuromuscular system part (NMS), representing body elements, and a cognitive part, the human cortex (HC), responsible for all cognitive control commands. The research presented in this paper focuses on the neuromuscular aspect of BDFT, thus only on the role of the NMS part of the human operator; cognitive actions are not considered. The scope of this study is further limited by investigating one specific type of BDFT systems only. In many manual control tasks, a human operator is piloting or steering a vehicle. In this case the control inputs of the HO influence the motion of the PLF, which is indicated by the dotted line in Figure 1. This type of biodynamic feedthrough system is labeled as a *closed loop* system. If the human operator is not influencing the motion of the platform by his control inputs (e.g. when pointing a camera on board of a moving vehicle) the system is called an *open loop* system. In this study only open loop BDFT systems are investigated.

III. MODELING THE INFLUENCE OF NEUROMUSCULAR ADMITTANCE ON BIODYNAMIC FEEDTHROUGH

Several approaches to mitigate biodynamic feedthrough have been suggested in literature [2][8][9][10]. A possible approach is to subtract the modeled effect of biodynamic feedthrough from the output of the control device before it enters the controlled element. This method is illustrated in grey in Figure 1 and is referred to here as the *control input cancellation method*. The eventual goal of this research is to design a cancelling controller using this approach.

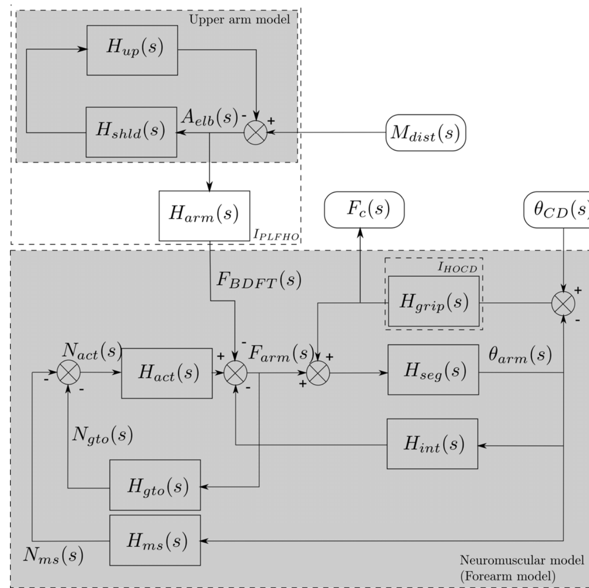

Figure 2. The biodynamic feedthrough model, consisting of a neuromuscular model, representing the forearm, and an upper arm model. The features contained in the neuromuscular model are: muscle activation dynamics (H_{act}), endpoint inertia (H_{seg}), intrinsic muscle stiffness and damping (H_{int}), reflexive force feedback (H_{gto}), reflexive stretch and velocity feedback (H_{ms}), and grip force dynamics (H_{grip}); s denotes the Laplace operator ($= j2\pi f$). For details concerning the neuromuscular model the reader is referred to [11] and [12]. The upper arm is modeled as a spring damper system. The H_{shld} block represents the damping and stiffness of the shoulder joint. The H_{up} block represents the mass of the upper arm and H_{arm} the mass of the forearm. M_{dist} represents the motion disturbance (accelerations) of the PLF. F_c is the contact force applied to the control device and θ_{cd} the control input (see Figure 1)

The control input cancellation method requires a BDFT model that is able to model the (unintentional) control inputs caused by the feedthrough of platform accelerations. The challenge in setting up such a model lies in modeling the feedthrough of accelerations through the body, the NMS, of the human operator. The NMS dynamics are commonly described by admittance, which is defined as the dynamic relation between a force input and a position output of a limb. Human admittance is adjustable through various mechanisms and is task dependent [11]. It is hypothesized that changes in admittance yield changes in biodynamic feedthrough as well. Furthermore, it is hypothesized a relationship can be established between neuromuscular admittance and biodynamic feedthrough, or, in other words: when the admittance is known, the BDFT can be determined. This hypothesis is based on the notion that in a given BDFT system the neuromuscular properties are the only variables present, and that thus a change in admittance, leads to a predictable change in BDFT.

In this study the arm is the control limb under consideration. Furthermore, in this study only lateral accelerations are considered and the model that is developed is limited to describe lateral motion only.

A. The neuromuscular model

Numerous neuromuscular models have been developed in the past. The NMS model used in this study is based on the models proposed in [11] and [12]. The neuromuscular model is shown in the lower box in Figure 2. Due to space limitations, the reader is referred to [11] and [12] for details concerning the neuromuscular model.

B. Incorporating biodynamic feedthrough in the neuromuscular model

The arm is modeled to consist of the upper arm and forearm. The wrist and hands are lumped in the forearm model. Figure 3 shows this arm model. The orientation of the arm is determined by the angle at the shoulder joint, θ_{up}, and the angle at the elbow joint, θ_{arm}. The dynamics of the forearm are modeled using the neuromuscular model, presented in the lower box in Figure 2. The upper arm is modeled as a mass-spring-damper system.

The upper arm model contains two elements: H_{shld}, representing the damping and stiffness of the shoulder joint, and H_{up}, representing the mass of the upper arm. Due to its inertia, the upper arm responds to the PLF acceleration by rotating around the shoulder joint. The resulting accelerations of the elbow, A_{elb}, work in turn on the forearm by means of a force, labeled the biodynamic feedthrough force F_{BDFT}. This force is calculated by multiplying the elbow accelerations with the mass of the forearm, represented by the H_{arm} block. F_{BDFT} forms the connection between the platform accelerations M_{dist} and the neuromuscular model, as is shown in Figure 2.

By inserting Figure 2 in Figure 1, replacing the NMS and I_{PLFHO} blocks, a detailed BDFT model is obtained. Before it can be used to provide insight in the relation between neuromuscular admittance and biodynamic feedthrough, it needs to be parameterized and validated first. In order to do this an experiment was conducted to measure both the biodynamic feedthrough dynamics and the neuromuscular admittance for different control tasks.

IV. Measuring the Influence of Neuromuscular Admittance on Biodynamic Feedthrough

A. Apparatus

The experiment was performed on the SIMONA Research Simulator (SRS) of Delft University of Technology. The SRS is a six degrees-of-freedom research flight simulator, with a hydraulic hexapod motion system. The control device was an electrically actuated side-stick. No arm rest for the hand that controlled the side-stick was present. A head-down display (15” LCD, 1024x768 pixels, 60Hz refresh rate) was located in front of the right hand pilot seat where subjects were seated during the experiment. The seat had a 5-point safety belt that was adjusted tightly in the experiments.

B. Subjects

Three male subjects and one female subject participated in this study with an average age of 23.3 years (SD of 3.3 years). Subjects were recruited from the student population of Delft University of Technology.

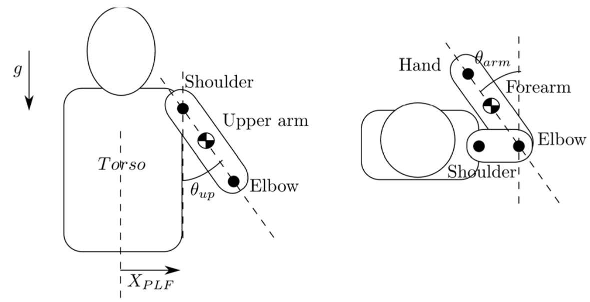

Figure 3. The arm is modeled to consist of an upper arm and a forearm. The upper arm is modeled as a mass-spring-damper system, the forearm is modeled using the linear arm model

C. Experiment task and task instruction

In the experiment, the subjects performed three different disturbance rejection tasks during which the side-stick was perturbed with a force disturbance F_{dist} (see also [11] and [13]):

- Position task (PT), in which the instruction is to keep the position of the side stick in the centered position, that is, to resist the force perturbations as much as possible;
- Force task (FT), in which the instruction is to minimize the force applied to the side stick, that is, to yield as much as possible to the force perturbations;
- Relax task (RT), in which the instruction is to relax the arm while holding the control stick, that is, to passively undergo the side-stick perturbations.

The human operator needs to set his/her neuromuscular properties differently for optimal control of each of the three control tasks. The PT is a task for which the best performance is achieved by being very stiff (i.e. a small admittance), the FT requires the operator to be very compliant (i.e. a large admittance). The RT is intended to yield an admittance which gives an indication of the passive dynamics of the neuromuscular system.

During the PT and FT, information was displayed on a screen in front of the subjects. A laterally moving red block displayed the parameter to be controlled and the goal position was shown by a white, vertical line running down the center of the display. During the PT, the controlled parameter was the lateral side stick deflection angle; during the FT this was the applied force to the side-stick. For both tasks the display also showed a time-history of position or force respectively, such that subjects could monitor their performance. During the RT the display presented no information.

To create a situation in which biodynamic feedthrough occurred the simulator motion system was used. Simultaneously with the side stick force perturbations F_{dist}, the simulator motion system generated lateral motion perturbations M_{dist}, see Figure 1.

Before entering the simulator, subjects were instructed on the goal of the experiment and the control tasks they were to perform. In the simulator, the subjects were seated in an aircraft seat with a side stick positioned to its right. First, several training runs were performed to allow the subject to get used to the force and motion disturbances and the different control tasks. The duration of each task was 87 seconds. When the subjects indicated to have understood the control tasks the measurements started.

D. Experiment design

1) Independent variables

Two independent variables were used: the control task (TASK) and a motion perturbation signal (DIST). The different levels for each independent variable were:

- TASK: Position task (PT); Force task (FT); and Relax task (RT)
- DIST: On; and Off

Together, TASK and DIST yielded six different conditions. First, the experiments with the motion disturbance signal were executed (i.e. DIST On). The control tasks were sequenced in the order PT-RT-FT. Four repetitions of this sequence were executed. Then, the conditions without motion disturbance (DIST Off) were executed, using the same control task sequence, PT-RT-FT, and three repetitions. For this preliminary study it was assumed that the influence of learning effects was negligible.

2) Perturbation design

The force disturbance signal F_{dist} was present in all runs. The motion disturbance signal M_{dist}, was only present in three of the six experiment conditions. Both disturbance signals were multi-sines, defined in the frequency domain. The phase of the sine components was randomized in order to obtain an unpredictable signal. A cresting technique was used to prevent large peaks in the time domain [14]. F_{dist} consisted of a continuous force command that was fed to the side-stick. M_{dist} consisted of a continuous acceleration command. F_{dist} was used to determine the neuromuscular admittance of the human operator. M_{dist} was used to determine the operator's biodynamic feedthrough dynamics.

Admittance and BDFT were measured simultaneously during the experiment. In order to allow the dynamics to be separated in the analysis, the disturbance signals were separated in the frequency domain. Figure 4 shows the spectral densities of the two disturbance signals, showing that the two signal contained power at different frequencies. By evaluating dynamics only at the frequencies where it was excited by a disturbance, the response to each disturbance signal was obtained [11], i.e. admittance was only evaluated at frequencies where F_{dist} was present; BDFT was only evaluated at frequencies where M_{dist} was present. The reduced power method was used to estimate full bandwidth dynamics [15].

3) Dependent measures

During the experiments the angular deflection of the side stick θ_{CD}, and the applied force to the side stick F_C were measured and F_{dist} was recorded from which an estimate of the human arm admittance $\hat{H}_{adm}$ could be made. From the measured θ_{CD} and F_C and the recorded M_{dist} an estimate of the biodynamic feedthrough dynamics, $\hat{H}_{bdft}$ could be made.

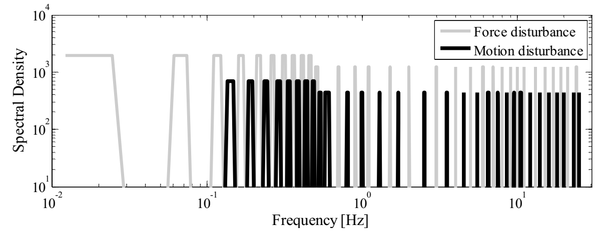

Figure 4. Spectral densities of the force disturbance signal and motion disturbance signal.

V. RESULTS

A. Admittance for the different control tasks

Figure 5 shows the FRF estimates of the admittance for a typical subject. The admittances shown here were measured without the motion disturbances present. As expected, the admittance for the FT is the largest and the admittance for the PT the smallest. The admittance for the RT lies approximately in-between. Furthermore, it can be seen that the admittance is differing most for the lower frequencies, as many of the mechanisms to adapt the neuromuscular admittance are most effective in the low-frequency range.

For both the PT and the FT, all subjects displayed a very similar admittance to the one shown in Figure 5. However, for the RT, more variation between subjects was observed and many of the subjects did not succeed in attaining a lower admittance than during the FT, yielding a very similar admittance for both the FT and RT. Probably, these subjects misunderstood the task instruction for the RT. The effect of the RT can therefore not be adequately investigated from this data set and will not be considered in the remainder of the analysis.

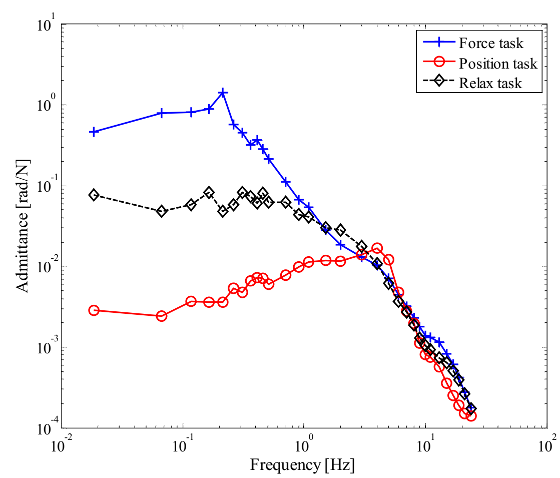

Figure 5. Measured admittance for the three control tasks, without motion disturbance present, for subject SdJ

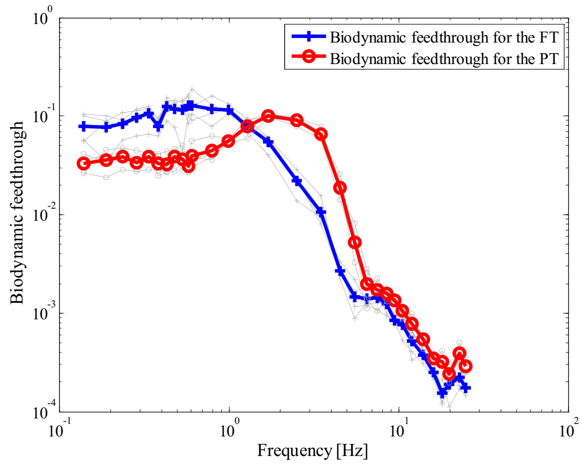

Figure 6 Measured biodynamic feedthrough for the FT and PT. The thin lines show the BDFT measured for the individual subjects, the thick lines show the average over all subjects.

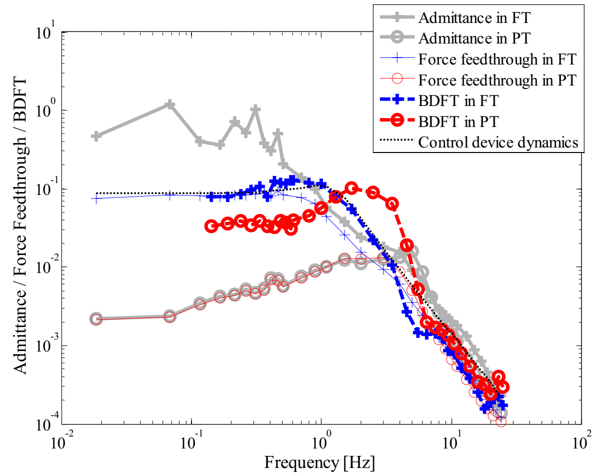

Figure 7 Averaged neuromuscular admittance, force feedthrough and biodynamic feedthrough for the three control tasks. Also the control device dynamics are shown.

B. *Biodynamic feedthrough dynamics for different control tasks*

Figure 6 shows the measured biodynamic feedthrough for the FT and the PT. Both the BDFT measured for the individual subjects, as the average over all subjects is shown. The BDFT was found to be very similar for all subjects, thus the average can be considered to represent the general response

For low frequencies (< 1.5 Hz) the biodynamic feedthrough is considerably lower during PT than during FT, meaning that the accelerations of the platform caused smaller deviations of the stick. Interestingly, for frequencies above 1.5 Hz the biodynamic feedthrough is larger for the PT than for the FT. Furthermore, a peak in biodynamic feedthrough can be observed for the PT, at approximately 2-3 Hz. For the higher frequencies (> 6 Hz) the difference in BDFT for both tasks becomes smaller, but still the level of feedthrough for the PT is slightly higher. The observed differences in BDFT can only be the result of adaptations of the neuromuscular system in response to the task instruction.

The results show that for disturbance frequencies above 1.5 Hz, more biodynamic feedthrough occurs during a PT than during a FT. This result is remarkable, because during a PT a stiff neuromuscular setting is used to reject (force) disturbances. The results suggest that the strategy attained during the PT to reject force disturbances, actually increases the feedthrough of motion disturbances above 1.5 Hz, in comparison to the strategy attained during the FT.

C. *Relating biodynamic feedthrough to neuromuscular admittance using force feedthrough*

When investigating in the influence of neuromuscular admittance on biodynamic feedthrough, it should be noted that the admittance only describes the dynamic response of the NMS, i.e. the transfer dynamics between θ_{CD} and F_C in Figure 1 (actually, that is the impedance; admittance is the inverse of impedance). Biodynamic feedthrough, however, describes the feedthrough of the applied motion disturbance to control device deflection, i.e. the transfer dynamics between M_{dist} and θ_{CD} in Figure 1. So, BDFT describes the combined dynamic response of the NMS and the CD to motion disturbances, while admittance only describes the dynamics of the NMS. Evidently, this prohibits direct comparison between admittance and BDFT. Therefore the concept of *force feedthrough* is introduced. Similar to biodynamic feedthrough, force feedthrough describes the feedthrough of disturbances to the control device deflection, but now for *force* disturbances F_{dist}, instead of M_{dist}. In Figure 1, force feedthrough is the transfer dynamics between F_{dist} and θ_{CD}. Force feedthrough can now be directly compared to biodynamic feedthrough, but it is also directly related to admittance, as it is simply the combined dynamic response of the NMS and the (known) CD. The admittance, the force feedthrough and the biodynamic feedthrough for both control tasks are shown in Figure 7.

The neuromuscular admittance and the force feedthrough dynamics are very similar for the PT, but very different for the FT. This can be explained looking at the control device dynamics (also shown in Figure 7). Because the neuromuscular system and the control device can be considered to be connected in parallel, it follows that the force feedthrough dynamics, i.e. the combined dynamics, are dominated by the stiffer element [1]. During the PT, the neuromuscular system is the stiffer element, so the force feedthrough dynamics are dominated by the admittance. For the FT the control device is the stiffer element, so the force feedthrough is dominated by these dynamics.

[1] To illustrate this consider two parallel springs, one having a high stiffness and one having a low stiffness. It can be easily seen that the dynamics are now dominated by the stiffer spring

VI. Discussion

The force feedthrough and biodynamic feedthrough share some similar general features. For the PT we see a shallow increase in feedthrough as frequency increases, until a certain peak frequency between approximately 2-3Hz, after which feedthrough decrease. For the FT, the force and biodynamic feedthrough share similar features as well: only a marginal effect of disturbance frequency on the feedthrough for low-frequencies, up to a bandwidth of approximately 1 Hz after which feedthrough steadily decreases. These similar trends suggest that a relation can be established between the force feedthrough and biodynamic feedthrough.

The concept of force feedthrough was introduced to facilitate the direct comparison between biodynamic feedthrough and neuromuscular admittance. The force feedthrough is directly related to neuromuscular admittance, because the control device dynamics are known and not varying in time, rendering the admittance the only variable. The similar trends that were observed between force feedthrough and biodynamic feedthrough, therefore, also suggest that there exists a relationship between biodynamic feedthrough and neuromuscular admittance, as was hypothesized earlier.

The BDFT model, proposed in section III, can be employed to find such a relationship and provide an explanation for the observations described in the previous paragraphs. To test the model its parameters need to be identified. This can be done by fitting the modeled response to the measured response. The parameter identification of the BDFT model is currently being performed, of which the results will be presented in future publications. The parameterized model will also be employed to develop a cancelling controller based on the control input cancellation method, shown in Figure 1.

VII. Conclusions

For a given BDFT system, biodynamic feedthrough is predominantly influenced by the neuromuscular admittance. At low frequencies, admittance is highly adaptive and dependent on factors such as intrinsic and reflexive feedback, the level of muscle co-contraction and task instruction. Therefore, the biodynamic feedthrough is highly adaptive and influenced by these factors as well.

The BDFT model developed in this paper incorporates the effect of biodynamic feedthrough in a neuromuscular model, which describes the neuromuscular admittance. In an experiment both the neuromuscular admittance and the biodynamic feedthrough were measured for different control tasks. For the FT and the PT very similar admittances and BDFT were measured for all subjects. It was observed that for low frequencies (< 1.5 Hz), the biodynamic feedthrough is considerably lower during PT than during FT. However, for disturbance frequencies above 1.5 Hz, more biodynamic feedthrough occurs during a PT than during a FT. The results suggest that the strategy attained during the PT, to reject force disturbances, actually increases the feedthrough of motion disturbances above 1.5 Hz, in comparison to the strategy attained during the FT.

When comparing the feedthrough of force disturbances and feedthrough of motion disturbances, some similar features can be observed, suggesting a relationship can be established between the force feedthrough and BDFT. As the force feedthrough is directly related to neuromuscular admittance the results support the statement that that there exists a relation between the admittance and BDFT.

The parameter identification of the BDFT model is currently being performed and will be presented in future publications. Subsequently, the parameterized model will be employed to develop a cancelling controller based on the control input cancellation method.

References

[1] Jex, H.R. and Magdaleno, R., "Biomechanical models for vibration feedthrough to hand and head for a semisuspine pilot" Aviation, Space, and Environmental Medicine, Vol. 49, No. 1, pp: 304–316, 1978

[2] McLeod, R. and Griffin, M., "A review of the effect of translational whole-body vibration on continuous manual control performance" Journal of Sound and Vibration, Vol. 133, No. 1, pp:55 – 115, 1989

[3] Banerjee, D., Jordan, M., and Rosen, M., "Modeling the effects of intertial reactions on occupants of moving power wheelchairs". Proceedings of the Rehabilitation Eng. and Assistive Tech. Soc. of North America Conf. (RESNA), pp: 220 –222, 1996

[4] Parker, N., Salcudean, S., and Lawrence, P., "Application of force feedback to heavy duty hydraulic machines". Proc. of the Int. Conf. on Robotics and Automation, pp: 375 – 381, 1993

[5] Arai F., Tateishi J., and Fukuda, "Dynamical analysis and suppresion of human hunting in excavator design", Proc. IEEE Int. Workshop Robot Human Interactive Commun., pp: 394-399, 2000

[6] Höhne, G., "A biomechanical pilot model for prediction of roll ratcheting". A Collection of the AIAA Atmospheric Flight Mechanics Conf. Technical Papers, pp: 187– 196

[7] M.M. van Paassen, "A model of the arm's neuromuscular system for manual control", Proc. Of the 6th IFAC symposium on Analysis, Design and Evaluation of Man-Machine Systems, pp. 681-685, June, 1995

[8] Dimasi, F., Allen, R., and Calcaterra, P., "Effect of vertical active vibration isolation on tracking performance and on ride qualities", NASA CR-2146, 1972

[9] Sövényi, S. and Gillespie, R., "Cancellation of biodynamic feedthrough in vehicle control tasks" IEEE Trans. On Contr. Syst. Tech., Vol. 15, No. 6, pp:1018 – 1029, 2007

[10] Velger, M., Grunwald, A., and Merhav, S.. "Adaptive filtering of biodynamic stick feedthrough in manipulation tasks on board moving platforms", J. of Guidance, Vol. 11, No. 2, pp:153 – 158, 1988

[11] Abbink, D.A., "Neuromuscular analysis of haptic gas pedal feedback during car following", (Phd) Faculty of Mechanical Maritime and Materials Engineering, Delft University of technology, 2006

[12] Lasschuit, J., Lam, T.M., Mulder, M., van Paassen, M.M., Abbink, D.A., "Measuring and modeling neuromuscular system dynamics for haptic interface design", Proc. of the AIAA Modeling and Simulation Technologies Conference and Exhibit, Honolulu (HI), 2008 (AIAA-2008-6543)

[13] Abbink, D.A., "Task Instruction: the largest influence on human operator motion control dynamics", Proc. Sec. Joint EuroHaptics Conf. and Symp. On Haptic Interfaces for Virt. Environment and Teleoperator Systems, Tsukuba, Japan, pp:206-211, 2007

[14] Pintelon, R., Schoukens, J., "System identification: A frequency domain approach", IEEE Press, New York, USA, 2001

[15] Mugge, W., Abbink, D.A., van der Helm, F.C.T., "Reduced power method: how to evoke low-bandwidth behaviour while estimating full-bandwidth dynamics", IEEE 10th Int. Conf. on Rehabilitation Robotics, pp: 575-581, 2007