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Biodynamic Feedthrough: Current Status and Open Issues

Joost Venrooij * Mario Olivari * Heinrich H. Bülthoff *

* Max Planck Institute for Biological Cybernetics, Department Human Perception, Cognition and Action, 72076 Tübingen, Germany (e-mail: {joost.venrooij,mario.olivari,heinrich.buelthoff}@tuebingen.mpg.de).

Abstract: Biodynamic feedthrough (BDFT) occurs when vehicle accelerations feed through the body of a human operator, causing involuntary limb motions, which in turn result in involuntary control inputs. Manual control of many different vehicles is known to be vulnerable to BDFT effects, such as that of helicopters, aircraft, electric wheelchairs and hydraulic excavators. This paper provides a brief review of BDFT literature, which serves as a basis for identifying the fundamental challenges that remain to be addressed in future BDFT research. One of these challenges, time-variant BDFT identification, is discussed in more detail. Currently, it is often assumed that BDFT dynamics are (quasi)linear and time-invariant. This assumption can only be justified when measuring BDFT under carefully crafted experimental conditions, which are very different from real-world situations. As BDFT dynamics depend on neuromuscular dynamics, they are typically time-varying. This paper investigates the suitability of a recently developed time-variant identification approach, based on a recursive least-squares algorithm, which has been successfully used to identify time-varying neuromuscular dynamics.

Keywords: biodynamic feedthrough, cybernetics, time-variant identification

1. INTRODUCTION

Manual control performance of tasks performed on board of moving vehicles can suffer from biodynamic feedthrough (BDFT). BDFT can be defined as the transfer of accelerations through the human body during the execution of a manual control task, causing involuntary forces being applied to the control device, which may result in involuntary control device deflections (Venrooij, 2014). The occurrence of closed-loop BDFT, where the human operator forms a closed loop with the vehicle by means of a control device, is schematically illustrated in Fig. 1. BDFT can also occur in an open-loop form, i.e., when there is no coupling between the vehicle and the control device. This can, for example, occur during writing and pointing tasks or during the interaction with a touch screen inside a moving vehicle.

Biodynamic feedthrough has been reported in literature to occur in various vehicles and under various circumstances. For aircraft and rotorcraft, BDFT is recognized as a problem for a variety of operations (Jex and Magdaleno, 1978; National Research Council, 1997; Pavel et al., 2015). An example of BDFT in helicopters is vertical bounce, where vertical accelerations cause involuntary control inputs at the collective pitch stick (Mayo, 1989). Also aircraft can suffer from BDFT under various conditions, for example when flying through atmospheric turbulence (Raney et al., 2001) or during roll-ratcheting: a high-frequency roll oscillation that can occur during roll maneuvers in high-performance (fighter) aircraft (Hess, 1998; van Paassen et al., 2004). Also hydraulic excavators (Humphreys et al., 2014) and electrically powered wheelchairs (Banerjee et al., 1996) are known to be prone to BDFT.

The fact that biodynamic feedthrough is leading to control problems in many different vehicles under many different circumstances makes it a relevant topic for research. Despite numerous research efforts, BDFT effects still degrade control performance for operators in, e.g., excavators, aircraft and helicopters. This indicates that, despite the progress that has been made, BDFT remains a complex phenomenon and current solution strategies are not always adequate. Continued efforts to improve our understanding will help us to reduce BDFT further, making vehicle-based operations safer and easier.

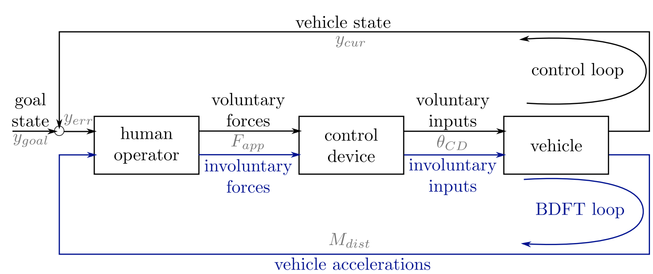

Fig. 1. Schematic of closed-loop biodynamic feedthrough. The human operator controls a vehicle by applying force F_{app} to a control device, which cause control device deflections θ_{CD}. BDFT occurs when vehicle accelerations M_{dist} cause involuntary control forces and control device deflections, in addition to the voluntary components.

The aim of this paper is to review the current state of BDFT research (Section 2) and discuss some of the most important open issues that are still to be addressed (Section 3). The problem of time-variant BDFT identification, a major issue, is addressed in more detail in Section 4.

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2. REVIEW OF BIODYNAMIC FEEDTHROUGH LITERATURE

In the following we provide a brief overview of the literature, organized along the themes: *measuring*, *modeling* and *mitigating* biodynamic feedthrough. The overview is in no way meant to be exhaustive, as that would take more space than is available here. Instead, we aim to present a broad overview of how the BDFT research field has developed in the past decades.

2.1 Measuring BDFT

Around the 1950s and 1960s the field of biomechanics saw a tremendous increase in research activity, mainly motivated by the advances in aviation and space exploration. The immense bibliographies on biomechanical research that appeared around that time, such as (Snyder et al., 1963) and (Jones, 1971), each with hundreds of entries, are a testimony to this increased interest.

A portion of the studies in the 1960s reported or investigated the biodynamic feedthrough phenomenon – Larue (1965) was one of the first – although the term ‘biodynamic feedthrough’ itself did not appear until much later. The extensive research reported by Allen et al. (1973) proposed partitioning human control behavior into three parts: the visual-motor response, the ‘vibration feedthrough’ (i.e., biodynamic feedthrough), and the remaining portion, or remnant, making it one of the first extensive research campaigns in which BDFT was explicitly investigated. The term “biodynamic feedthrough” started to appear in the 1980s (Jewell and Citurs, 1984) and the considerable progress that was made on the topic by the end of the 1980s is illustrated in the review paper by McLeod and Griffin (1989) and in the ‘Handbook of Human Vibration’ by Griffin (1990). The former provides a comprehensive review of BDFT related literature, the latter provides a comprehensive discussion of the different mechanisms by which exposure to vibrations affects the human body.

Recently, two European research projects – GARTEUR HC-AG16 (Dieterich et al., 2008) and ARISTOTEL (Pavel et al., 2015) – investigated adverse Aircraft/Rotorcraft-Pilot Couplings (A/RPCs). A/RPCs are unwanted phenomena originating from an anomalous/undesirable discord between the pilot’s intentions and the aircraft’s response. It is known that BDFT can both cause and sustain such events. This illustrates that BDFT is, still, an unsolved and relevant issue. Other recent work on measuring BDFT is (Venrooij et al., 2011), in which a new time-invarient method to simultaneously measure BDFT and neuromuscular dynamics is proposed.

2.2 Modeling BDFT

In the early 1970s, the first physical BDFT models appeared, such as (Allen et al., 1973; Jex and Magdaleno, 1978, 1979). These models were primarily constructed using a-priori knowledge and physical principles. The models were typically validated using experimental data of the biodynamic response of body parts to vibration disturbances of varying magnitude and frequency.

Black box models, in contrast, describe the relationship between input and output without considering the physical elements in between. Examples of black box BDFT models can be found in (Velger et al., 1984; Mayo, 1989; Sövényi, 2005). The main advantage provided by physical BDFT models over black box BDFT models is the additional insight gained in the physical processes underlying the BDFT phenomena. However, they are usually more elaborate than their black box counterparts, which complicates their parametrization, implementation and proper use.

The development of new physical and black box BDFT models still continues. Examples of recent physical BDFT models can be found in (Venrooij et al., 2014a) and (Masarati et al., 2015), new black box BDFT models were recently proposed in (Humphreys et al., 2014) and (Venrooij et al., 2014b).

2.3 Mitigating BDFT

A main motivator for BDFT research is the desire to *reduce* the BDFT effects on manual control performance. Torle (1965) was one of the first to study BDFT mitigation by investigating the mitigating effect of an armrest. A much more complex active vibration isolation system was developed in (Schubert et al., 1970), in which the human operator is isolated from vehicle accelerations by actively compensating for platform accelerations. An adaptive filtering technique was proposed by Velger et al. (1984) and tested in (Velger et al., 1988). Results of another approach, force reflection, which cancels BDFT effects by opposing involuntary forces, are presented in (Repperger, 1995) and (Sövényi, 2005). Sirouspour and Salcudean (2003) proposed a robust controller to suppress BDFT effects using μ-synthesis. For a more elaborate review of the possible BDFT mitigation methods, the reader is referred to (Venrooij et al., 2010).

BDFT mitigation is still an active research area. The effectiveness of an armrest in BDFT mitigation was recently studied in (Venrooij et al., 2012a). Humphreys et al. (2014) proposed a controller-based BDFT compensation for backhoe excavators. For air- and rotorcraft, Pavel et al. (2015) proposed methodologies, such as design recommendations, to preclude A/RPC events, some of which relate to preventing or mitigating BDFT. Venrooij et al. (2014c) proposed and successfully evaluated an admittance-adaptive model-based approach to BDFT cancellation. The novelty of this mitigation method is that it accounts for changes in the neuromuscular dynamics.

3. OPEN ISSUES

In the following, we discuss three selected issues, concerning measuring, modeling and mitigating BDFT, that deserve further attention.

3.1 Measuring BDFT: time-variant identification

The system identification techniques used for the identification of BDFT dynamics are typically limited to linear time-invariant (LTI) applications. Only with carefully designed experimental conditions can one justify the assumption that the measured dynamics are linear around a constant operating point and are time-invariant for the duration of the measurement. As a result, most of what