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Frequency-domain iterative learning control of a marine vibrator

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ABSTRACT

To the purpose of marine seismic acquisition, new acoustic sources have been developed to reduce the environmental impact. The use of marine vibrators makes it possible to define emission frequency ranges, consequently allowing limitation of the frequencies that disturb marine animal life. Constructing marine vibrators with high efficiency and linear dynamics is however difficult, and the vibrators suffer from both friction, backlash and high-order harmonics. These nonlinear effects, in combination with drifting dynamics, make the required control a crucial and challenging problem. This paper presents a model-based iterative learning control solution, performed in the frequency-domain. Additionally, an adaptive reidentification algorithm is developed to cope with drifting dynamics. The proposed solutions are successfully evaluated in experiments with a marine vibrator.

1. Introduction

In the areas of marine seismic acquisition, the use of acoustic sources such as impulsive sources have been dominating for several decades. However, recent developments of marine vibrators offer numerous advantages, if the device is controlled properly. Marine vibrators are environmentally friendly, because of the reduced peak source strength in terms of pressure, compared to an impulsive source. The frequency content can be controlled such that there is less impact on marine mammals outside the seismic band. The frequency range of interest for the signals that are to be emitted from the marine vibrator is approximately 5–100 Hz. It is crucial that only these frequencies are emitted, as higher frequencies may interfere with marine animal life (LGL & MAI, 2011). However, since marine vibrators are advanced mechanical systems, nonlinear effects and high-frequency harmonics are likely to be present. The marine vibrator considered in this paper has been found to produce high-energy overtones, which need to be attenuated in order to fulfill the specifications. The contribution of this paper is the modeling and control of such a marine vibrator, to the purpose of overtone attenuation and reference tracking. A model-based iterative solution is presented, based on frequency-domain iterative learning control (ILC), considering both single-input single-output (SISO) and multi-input multi-output (MIMO) cases. Additionally, a method for adaptive reidentification of the vibrator model for diverging frequencies is presented.

1.1. Previous research

The mechanical design of marine vibrators, including the driving means and measurement systems, has thoroughly been researched in, *e.g.*, Graydon and Delbert (1969), Tenghamn (2006), and Tenghamn (2009). The aspect of precise position control of marine vibrators is however not as well represented in the literature. In Tenghamn (2011), a time-domain ILC scheme for vibrator position control is proposed. However, no results are presented.

The subject of ILC has been comprehensively researched. It was initially introduced in a Japanese journal in 1978 (Uchiyama, 1978), but it did not reach a broad audience until 1984. Three different papers were then simultaneously published (Arimoto, Kawamura, & Miyazaki, 1984; Casalino & Bartolini, 1984; Craig, 1984), in which improving position control of robotic manipulators by iterative learning were considered. In the thesis (Norrlöf, 2000), further development of the ILC algorithm is presented. General surveys of ILC methods, theory, and applications are found in Bristow, Tharayil, and Alleyne (2006) and Ahn, Chen, and Moore (2007).

For the application considered in this paper, frequency-domain ILC was found to be immensely superior to time-domain ILC, see Section 7. Convergence properties of ILC algorithms in the frequency domain are analyzed in Goh (1994) and Norrlöf and Gunnarsson (2002). A couple of different applications of the frequency-domain inversion-based ILC approaches have been considered previously; nanopositioning applications are developed in

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Yan, Wang, and Zou (2012) and Tien, Zou, and Devasia (2005) and acoustic noise reduction is investigated in Waite, Zou, and Kelkar (2008).

A modeling-free inversion-based ILC algorithm is presented in Kim and Zou (2008) and Kim and Zou (2013), where the frequency-domain input/output relation is used in each iteration to eliminate model dependence. The algorithm was applied to a nanofabrication scenario in Yan, Zou, and Lin (2009). This method is, however, not applicable to the scenario considered in this paper, as sufficient excitation is not provided in the complete frequency compensation range. Instead, an adaptive reidentification algorithm is developed in this paper, in order to cope with process variations.

1.2. *Disposition*

This paper is organized as follows. Section 2 describes the objectives of marine seismic acquisition, followed by a description of the hardware in Section 3. Control-system design principles are developed in Section 4, and modeling and control design are presented in Section 5. Results from experiments performed in air are presented in Section 6, followed by a comparison to time-domain ILC in Section 7. Finally, the method and experimental results are discussed, and conclusions are drawn in Section 8.

2. Marine seismic acquisition

Reflection seismology is used by petroleum geologists and geophysicists to map and interpret potential petroleum reservoirs. Oil and gas explorers use seismic surveys to produce detailed images of the various rock types and their location beneath the sea floor. This information is then used to determine the location and size of oil and gas reservoirs. The size and scale of seismic surveys have increased alongside the significant increases in computer power during the last 30 years. This has led the seismic industry from laboriously, and therefore rarely, acquiring small 3D surveys in the 1980s, to now routinely acquiring large-scale high resolution 3D surveys. The goals and basic principles have remained the same, but the methods have slightly changed over the years. Traditional marine seismic surveys are conducted using specially-equipped vessels that tow one or more cables containing a series of hydrophones located at constant intervals, see Fig. 1. The cables are known as streamers, with 2D surveys using only one streamer and 3D surveys employing up to twelve or more. The streamers are deployed just beneath the water surface, at a fixed distance from the vessel. The seismic source, traditionally an impulsive source or an array of impulsive sources, is also deployed beneath the water surface and is located between the vessel and the first receiver. Marine seismic surveys generate a significant quantity of data, since each streamer can be more than 8 km long, containing hundreds of channels, and the seismic source is typically fired every 10 or 20 s.

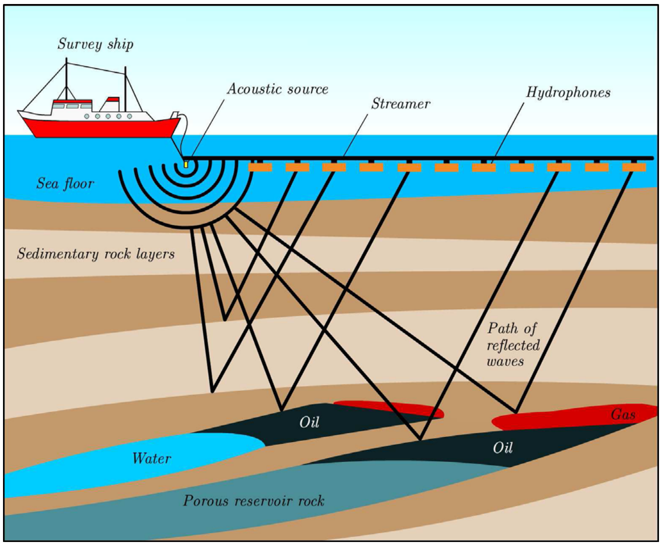

Fig. 1. Illustration of the marine seismic acquisition principle.

3. Marine vibrators

The considered marine vibrator, in this paper also referred to as a *transducer*, uses a *flextensional shell* to facilitate the low-frequency application, with an intended frequency range of 20–100 Hz. The transducer drivers are based on electrical coils operating in a magnetic field and spring elements that transfer the force from the electrical driver to the flextensional shell, see Fig. 2. The input to the marine vibrator is thus the driving current to the electrical coils, which displace the shell so that acoustic signals, *i.e.*, the output of the system, can be generated. Methods on how to measure the output are discussed later in this section.

Low-frequency sources face the problem of poor efficiency if a good impedance match with the surrounding water cannot be achieved. Straightforward calculations on the radiation from a vibrating piston with a radius of 0.3 m and a source level of 195 dB (rel. 1μPa), yields 0.074% efficiency at 10 Hz. The same piston has an efficiency of 99.9% at 10 kHz (Kinsler, Frey, Coppens, & Sanders, 1999). This leads to differentiator-type characteristics for the low-frequency dynamics of the system.

The mechanical construction of the considered marine vibrator (Fig. 4) exhibits two resonances; the lowest resonance originates from the shell interacting with the equivalent fluid mass and the second resonance from the spring elements with a resonance frequency in the upper frequency band. Having two resonances separated in the frequency band of interest makes it possible to achieve high efficiency. Additional details on the mechanical design of the vibrator are found in Tenghamn (2006).

A marine vibrator offers environmental advantages over impulsive sources. Given the high-profile environmental discussions on output peak power of seismic sources, vibrator technology offers a superior solution by spreading the energy in time, thus reducing the acoustic peak power. Additionally, the fact that a marine vibrator can generate arbitrary signals makes it useful for various types of spread-spectrum signals that can reduce the environmental impact even further.

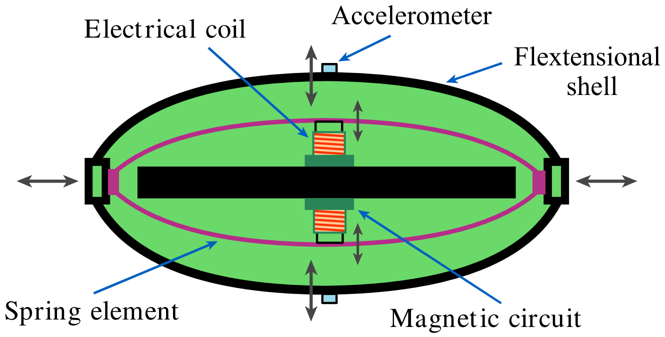

Fig. 2. Schematic drawing of the transducer actuation principle. The two flextensional shells are moved by the electrical coils via a construction of springs. This spring construction creates resonances at suitable frequencies, in order to improve the impedance match to the water, thus increasing the vibrator efficiency for low frequencies.