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A novel multipitch measurement algorithm for acoustic signals of moving targets

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ABSTRACT

In this paper, a novel multipitch measurement (MPM) method is proposed for acoustic signals. Starting from the analysis of moving targets' acoustic signatures, a pitch-based harmonics representation model of acoustic signal is put forward. According to the proposed harmonics model, a modified greatest common divisor (MGCD) method is developed to obtain an initial multipitch set (IMS). Subsequently, the harmonic number vector (HNV) associated with the IMS is determined by maximizing the objective function formulated as a multi-impulse-train weighted symmetric average magnitude sum function (SAMSF) of the observed signal. The frequencies of SAMSF are determined by the target acoustic signal, the periods of the multi-impulse-train are governed by the estimated IMS harmonics and the maximization of the objective function is figured out through a time-domain matching of periodicities of the multi-impulse-train with that of the SAMSF. Finally, by using the obtained IMS and its HNV, a precise fundamental frequency set is achieved. Evaluation of the algorithm performances in comparison with state-of-the-art methods indicates that MPM is practical for the multipitch extraction of moving targets.

1. Introduction

Ground vehicles (wheeled vehicles or tracked vehicles) and low-altitude propeller-driven aircrafts are the moving acoustic sources of focal interest to land-based monitoring systems, nevertheless they are out of the monitoring capability of radars, thus, the unattended ground sensors system (UGS) which is consisted by a lot of sensors, is responsible for recording, detecting and recognizing them [1]. Owing to the high levels of acoustic energy radiated by the engines of vehicles and by the propulsion systems of propeller-driven aircraft, these acoustic signals are possible to be recorded by a single microphone mounted close to ground. Measurement of multipitch (also called as multiple fundamental frequencies or *F*0s) contained in the acoustic signal of moving targets has a wide range of applications in motion parameters estimation [2,3], targets classification [4] and mechanical diagnosis [5,6]. For example, an aircraft can be determined whether it belongs to a piston engine aircraft based on the ratio of engine fundamental frequency and propeller blade passing fundamental frequency [5].

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Now, more and more research institutes are planning to make use of multipitch information of moving targets in many innovation applications, such as smart transportation [7] and IoT analytics platform [8].

The determination of fundamental frequency is a basic issue in signal processing. A reliable algorithm for multipitch estimation is critical for many applications [9–13], especially for speech recognition [14,15]. Hence, computational methods for multipitch estimation have received various attentions [14,16–18], besides many algorithms are available for estimating the single pitch in voice speech signals [19–21]. However, it is considered those pitch estimation algorithms [10–13] are not appropriate as such for the acoustic signals of moving targets, because of acoustic signals' narrower bandwidth, longer propagation distance and more complicated environmental noise in comparison with the conventional speech signal [22–24]. Since few algorithms are developed directly for moving targets' acoustic signal, this paper aims at extracting multiple fundamental frequencies for moving targets.

Based on the achievements of speech signal processing, this paper attempts to develop a comprehensive multipitch estimation method which combines the time-domain (TD) methods and frequency-domain (FD) methods. The main idea is to extract an initial multipitch set (IMS) followed by estimating a more accurate set from the harmonic number vector (HNV) corresponding to the IMS. In view of this, first, the signatures of acoustic signal are analyzed and a pitch-based harmonics presentation model is developed. Subsequently, the IMS is extracted by a modified greatest common divisor method (MGCD) which conducts signal in the FD-domain. Afterward, two TD-domain functions, the symmetric average magnitude sum function (SAMSF) [19] and the multi-impulse-train function (MITF) are applied to formulate an objective function. The maximization of the objective function through a time-domain matching of the periodicities of the multi-impulse-train with that of the SAMSF results in the HNV associated with the IMS. Finally, by using the obtained IMS and its HNV, a precise fundamental frequency set is achieved. In the proposed SAMSF weighted multi-impulse-train matching (S-MIT) scheme, since several local maxima instead of a single local maximum of the SAMSF are utilized, it can effectively avoid inaccurate estimation of the desired harmonic number. Through combining the low-computation advantage of TD methods (SAMSF and MITF) and the high-accuracy superiority of FD method (MGCD), the proposed method is compact and accurate. Experimental results demonstrate that the proposed method is capable of estimating multipitch accurately and efficiently, not only for a propeller-driven aircraft flying in the air, but also for a vehicle moving on the road.

This paper is organized into five sections including the present one. Section 2 analyzes the signatures of acoustic signal, and develops a pitch-based harmonics presentation model. Section 3 illustrates the principle of multipitch measurement method. In Section 4, the performances of the proposed method are presented through comparing with other methods. Finally, in Section 5, some distinctive features of this investigation are highlighted.

2. Acoustic signatures and harmonic model of moving targets

A moving target's acoustic signal consists of a combination of various sounds generated by engine, propulsion system, exhaust system, aerodynamic effects and mechanical effects, which can be modeled as a combination of two main components, deterministic component and nondeterministic component [4,25]. Specifically, the engine, propulsion system and exhaust system are responsible for the deterministic component, which can be represented using a coupled harmonics signal model [4].

2.1. Acoustic sources of moving targets

2.1.1. Engine

The sound from an internal combustion engine contains a stochastic component and a dominant sequence of harmonics so it can be modeled by the same methods used in human speech [26]. On one hand, the dominant component is caused by the fuel combustion in the engine cylinders and has larger power than the stochastic component. On the other hand, the stochastic component of the engine sound is largely due to the turbulent air flow in the air intake (or intercooler), the engine cooling systems and the alternator fans, so the stochastic component is wideband in nature.

The fundamental frequency of engine sound F_{engine} is related to cylinder fire rate $f_{cylinder}$ in a simple manner as follows:

$$F_{engine} = f_{cylinder} \times N_c, \tag{1}$$

where N_c is the number of cylinders in the engine, $f_{cylinder}$ is the firing rate of cylinder. In a four-stroke engine, the crankshaft rotates twice for each cylinder firing, therefore there is a simple relationship between $f_{cylinder}$ and the revolutions per minute (RPM) [25] as follows:

$$f_{cylinder} = \frac{RPM}{60 \times 2}, \tag{2}$$

Consequently, the fundamental frequency of this mechanism can be expressed as

$$F_{engine} = \frac{N_c \times RPM}{60P}, \tag{3}$$

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