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A linearly-acting variable-reluctance generator for thermoacoustic engines

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ABSTRACT

A crucial element in a thermoacoustic power converter for reliable small-scale power generation applications is an efficient acoustic-to-electric energy converter. In this work, an acoustic-to-electric transducer for application with a back-to-back standing wave thermoacoustic engine, based on a linearly-acting variable-reluctance generator is proposed, built and experimentally tested. Static and dynamic experiments are performed on one side of the generator on a shaker table at 60 Hz with 5 mm peak-to-peak displacement for performance characterization. A theoretical and empirical model of the variable-reluctance generator are presented and validated with experimental data. A frequency scaling based on the empirical model indicates that a maximum power output of 84 W at 78% generator efficiency is feasible at the thermoacoustic engine's operating frequency of 250 Hz, not considering power electronic losses. This suggests that the linearly-acting variable-reluctance generator can efficiently convert high frequency small amplitude acoustic oscillations to useful electricity and thus enables its integration into a thermoacoustic power converter.

1. Introduction

Thermoacoustic engines (TAEs), because of their lack of moving parts, show promise for reliable small-scale power generation. These engines convert thermal energy to mechanical energy in the form of large amplitude acoustic pressure oscillations. Due to the closed system nature of these engines, the heat addition to the hot heat exchanger is independent of the energy source and can come from combustion, waste heat or solar energy. A variety of engines of this type have been developed and examined in the past few years [1]. There are two inherently different types of TAEs, the standing wave and the traveling wave engine. The phasing of the heat transfer into the working fluid to the physical motion of the fluid is what differentiates the two. A standing wave engine consists of a straight resonant tube, a hot and cold heat exchanger and a stack. In this type of TAE the working fluid undergoes a Brayton cycle that limits the TAE's second law efficiency to 10–25% [2]. Nevertheless, this engine has received attention due to its simplicity and compactness. The traveling wave engine consists of a looped tube, a hot and cold heat exchanger and a regenerator. The ideal cycle associated with this engine type is the Stirling cycle that enables higher efficiencies.

The first investigations on the simplest forms of thermoacoustic engines date back to the studies of the generation of pressure waves in heated glass tubes by Sondhauss and Rijke. Sondhauss studied the conduction driven generation of pressure oscillations in glass tubes closed at one end [3], whereas Rijke studied the convection driven generation of pressure oscillations in open glass tubes [4]. This thermoacoustic phenomenon was then further studied and analyzed by Rayleigh [5], whose work built the basis for the linear acoustics theory, that was later developed by Rott [6], and which is still currently used for the analysis and design of thermoacoustic engines. Since then researchers have found ways to amplify the acoustic power in a standing wave engine by inserting a differentially heated stack in the engine's tube [7]. Ceperley was first to notice that in a traveling wave thermoacoustic engine arrangement the gas undergoes a Stirling cycle [8]. Only later though researchers demonstrated the amplification of acoustic power in such an engine [9]. The feasibility of higher engine efficiency was demonstrated by Backhaus and Swift, who introduced a smaller thermoacoustic Stirling engine based on a lumped impedance torus that created the same traveling wave phasing in the engine's regenerator [10]. Since this breakthrough in thermoacoustic technology much research has gone into improving the

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Nomenclature

Greek letters	
η	efficiency
λ	flux linkage
ϕ	magnetic flux
ρ	resistivity
θ	pulse duration
φ	oscillation phase angle
English letters	
$\mathcal{R}$	magnetic reluctance
$\mathcal{V}$	volume
A	cross-sectional area
B	magnetic flux density
b	thickness
f	oscillation frequency
H	magnetic field
h	height
I	current
L	inductance
l	length
m	mass
N	number of windings
P	power
R	resistance of coil
t	time
V	voltage
x	air gap length
Subscripts	
lam	lamination
max	maximum valued
min	minimum value
net	net
off	turn-off
on	turn-on
pw	piston wedge
s	steel
sat	value at saturation onset
sw	stator wedge
tot	total
w	winding
Acronyms	
TAE	thermoacoustic engine
TAPC	thermoacoustic power converter
VRG	variable-reluctance generator

traveling wave engine. For example Tijani et al. built a similar type of engine based on a lumped impendance torus [11] and with a redesign the engine a record efficiency of 49% of Carnot efficiency was demonstrated [12]. Other researchers have looked at developing traveling wave engines for new applications. A hybrid two stage traveling wave engine for low operating temperatures as used for waste heat energy harvesting was introduced by de Blok [13]. Engines powered with solar energy include a traveling wave engine developed by Wu and co-workers for electricity generation using linear alternator transducers [14] and a double-acting traveling wave engine developed by Zhang et al. [15]. Furthermore, a low cost concept of a traveling wave engine was demonstrated by Yu and co-workers [16].

In most of these applications though, an electric power output is preferable to the intrinsic acoustic power output of a TAE. As a consequence, thermoacoustic power converters (TAPC) generally include an acoustoelectric transducer to convert the acoustic power to electric power. Acoustic loudspeakers have been used in some early designs by Marrison, who coupled a loudspeaker to a standing wave engine without a stack [17], and Hartley, who coupled a loudspeaker to a convection-driven standing wave engine [18]. Engines developed for low cost also used loudspeakers such as the engine designed by Yu et al. [16], which in more recent work was further optimized to reach higher power output [19]. In all these designs the acoustic-to-electric efficiency was relatively low, with the highest value at 50% in an engine with a poor overall efficiency [16]. In many small-scale applications piezoelectric alternators have been used for transduction in thermoacoustic power converters. Keolian and Bastyr proposed different realizations of piezoelectric alternators using diaphragms for a thermoacoustic Stirling power converter [20]. A standing wave engine based on a push–pull concept with a piezoelectric transducer was investigated by Jensen and Raspet [21]. Another standing wave engine developed by Smoker et al. included a Helmholtz cavity in the engine's tube, which made piezoelectric membranes particularly suitable for acoustic-to-electric transduction [22]. A different type of thermoacoustic power converter based on a Rijke tube was developed by Zhao and also used a piezoelectric diaphragm [23]. In these power converters piezoelectric transducers enabled transduction with essentially no moving parts and at high frequency due to their small mass, which enhances the converter's power density. However, a theoretical analysis suggests that the low quality factor and low electromechanical coupling limits piezoelectric transduction to low acoustic-to-electric efficiencies [24], with a highest experimentally demonstrated efficiency of 22% [23].

Alternatively, in many applications linear alternators have been used for transduction in thermoacoustic power converters. In a converter design for space missions a linear alternator of a cryocooler pump was used coupled to a thermoacoustic Stirling engine [25]. Another version of this converter employing linear alternators was later developed to reach higher power output [26]. A thermoacoustic traveling wave engine designed specifically for high power output with a linear alternator was developed by Wu et al. [27]. Rossi et al. analyzed different available linear alternators for an optimal application in thermoacoustic engines using FEM simulations [28]. The influence of the mechanical resistance on the linear alternator transduction was investigated theoretically and experimentally by Gonen and Grossman [29]. The demonstrated transduction efficiencies of these linear alternators have so far surpassed corresponding values of other transduction methods, with a highest demonstrated acoustic-to-electric efficiency of up to 75% in an engine [25] and 91% on an alternator test rig [30], achieving high power density in the TAPC, because of better electromechanical coupling. These previously used linear alternators for thermoacoustic power converters or coolers were usually moving coil type [25] or moving magnet type generators [29,28,30]. However, the operating frequency of the engine in these designs is limited by the relatively large moving mass of the alternator. Another type of linear alternator proposed for thermoacoustic power converters is a variable-reluctance generator [31]. Since no moving magnets or coils are used in this type of linear alternator, a higher operating frequency can be achieved, and thus higher power density, due to the smaller moving mass.

In this work, an acoustic-to-electric transducer was designed and tested for use in a high frequency TAPC. The transducer is a