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Effect of variable mechanical resistance on electrodynamic alternator efficiency

Eran Gonen [a,*], Gershon Grossman [b]

[a] Qnergy, Ein Harod Ihud 1896000, Israel
[b] Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

The rapidly growing energy market constantly discovers new alternatives for generating environmentally-friendly electricity from sustainable energy sources. An externally-heated traveling wave thermo acoustic Stirling heat engine is a leading candidate, operating using a variety of viable heat sources. Although this engine holds great promise for a low-cost and maintenance-free solution, its current reported efficiency still inhibits its market penetration, probably owing to the friction introduced by the single moving element – the linear alternator.

This research quantifies the main parameters affecting the complex thermal–acoustical–electrical system, clarifying the critical role of frictional losses. An analytical model has been developed, enabling examination of the influence of the critical physical parameters on the electro-acoustic conversion efficiency. A measurement method for precise determination of the mechanical friction constant has been developed, which enables measuring the friction at the engine's working frequency. A direct measurement of an engine's transfer impedance at room temperature enables to find the exact natural frequency before field operation, and calibrate external hardware accordingly. A detailed simulation using DeltaEC™ indicates that the tight seal gap between the moving piston and its cylinder has a significant impact on the system's overall efficiency.

1. Introduction

Efficient Thermo Acoustic Stirling heat Engines (TASE), allowing for reliable operation without moving parts or sliding seals, have recently stirred a revival of interest. These environmentally-friendly, externally-heated engines may operate using a variety of viable heat sources, including natural gas, biofuels, open fire or solar radiation. Additionally, the lack of need for complex fabrication processes in the simple TASE structure makes it an excellent candidate for commercial solar electricity production. Nowadays, the rapidly growing solar-thermal market finds great promise in new methods for converting Concentrated Solar Power (CSP) into electricity.

The "traveling wave" thermo-acoustic engine employs the inherently reversible Stirling cycle, theoretically capable of attaining Carnot efficiency. A practical demonstration of a thermoacoustic engine has produced a thermal efficiency (heat to acoustic power) of 30% [1] at 725 °C, comparable to that of modern internal combustion engines [2] (25–40% heat to mechanical power). Converting acoustic power into mechanical and/or electrical power is no small challenge, and forms the subject of this work. A commercial thermoacoustic system has produced over 17 kW of acoustic power [3] which was then used to liquefy natural gas (Methane liquefies at 115 K at atmospheric pressure) at a rate as high as 140 gpd. In 2004, a remarkable thermoacoustic engine, converting heat into electricity, was developed by Northrop Grumman Space and Technology group with Los Alamos National Laboratory under a NASA contract [4]. This engine produced 39 W of electrical power at 18% overall conversion efficiency (heat to electricity), where a pair of dual opposed linear alternators were driven by acoustic power [5]. Using Inconel 625 for the hot heat exchanger has allowed working temperatures as high as 650 °C which enabled the first implementation of a traveling wave thermoacoustic engine for efficient electricity production.

Higher power levels have been demonstrated in 2005 by Luo et al. [6], as the nonlinear dissipation losses were reduced in the acoustic resonator by employing a tapered resonance tube. In 2008 [7] more than 100 W electrical output power were produced through proper coupling between the linear alternator and the thermoacoustic engine, and in 2011 [8] the electrical output power was further increased to as much as 481 W with thermal to

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* Corresponding author. Tel.: +972 524570951; fax: +972 46486946.
E-mail address: erangon@tx.technion.ac.il (E. Gonen).

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Nomenclature

A	cross section area, m^2
B	magnetic field, T
(Bl)	alternator constant, N/A
C	compliance, m^3/Pa
C_e	capacitance, F
F	force, N
f	frequency, Hz
I, I_1	total (real), oscillatory part (complex), of electrical current, A
I_a	acoustic intensity, W/m^2
K, $K_{gas\text{-}spring}$, K_{eff}	spring constant (mechanical), gas spring, effective, N/m
L	inertance, kg/m^4
L_e	electrical inductance, H
l	characteristic or effective length, m
m	mass, kg
p, p_m, p_1	total, mean part (real), oscillatory part (complex) of pressure Pa, (N/m^2)
$\vec{r}$	Power, W
R, R_e, R_L	electrical resistance (internal, external load), Ω
R_m	mechanical damping, N-s/m
R_r	acoustic flow resistor, N-s-m^3
$\vec{r}$	space vector, m
T, T_m, T_1	total, mean part (real), oscillatory part (complex) of temperature, K
t	time, s
U, U_1	total (real), oscillatory part (complex), of volumetric flow rate, m^3/s
u, u_1	total (real), oscillatory part (complex), x component of velocity, m/s
V	volume, m^3
V_{EMF}, V_1, V_{int}	voltage, V
$\vec{v}$	velocity vector, m/s
x	axial coordinate, m
y, z	transverse coordinate, m
Z_a, Z_{ALT}	acoustic impedance (total, acoustic representation of alternator impedance), N-s/m^5
$Z_{e,int}$, $Z_{e,ext}$, $Z_{e,total}$	electrical (internal, external, total) impedance, Ω
Z_m^e, Z_a^e	electrical equivalent of mechanical, acoustic impedance, Ω
Z_c	transfer impedance, A-s/m
Z_m, $Z_{m,a}$	mechanical impedance (total, mechanical–acoustical), N-s/m
γ	c_p/c_v adiabatic ratio
η	efficiency
ξ	displacement, m
ρ, ρ_m, ρ_1	total, mean part (real), oscillatory part (complex) of density kg/m^3
$\phi_{p_1,U_1}, \phi_{\Delta p_1,U_1}$	phase between p_1 or Δp_1 and U_1
ω	angular frequency 1/s

Supplementary notation

$\Re\{\}$	real part
$\Im\{\}$	imaginary part
$\|\|$	absolute value, Norm
$()^*$	complex conjugate
i	$\sqrt{-1}$
$\langle\rangle$	time average
Δ	difference

Subscript

AE	acoustic-electrical
ALT	alternator
a	acoustic
c	characteristic
CS	compression space
EMF	electromotive force
e	electric
ext	external
EA	electro-acoustic
int	internal
m	mechanical
m, a	mechano-acoustic
REG	regenerator
TA	thermoacoustic
TASE	Thermo Acoustic Stirling Engine
1	oscillatory variable

electricity efficiency of 12.65% at 650 °C, using 3.5 MPa pressurized helium at typical engine working conditions.

Additional recent projects include the work done at the Energy Research Center of the Netherlands (ECN) by Tijani and co-workers [9–11] ; the FP7 cooperative project on thermoacoustic technology for energy applications led by Spoelstra, Thermeau, Jaworski and de Blok [12–14]; the power converter built by Telesz at Georgia Institute of Technology [15]; the large-scale-engine research performed by Qiu et al. at the Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou, China [16];the investigation of low cost regenerator materials conducted by Yu, Jaworski and Abduljalil at the School of Mechanical, Aerospace and Civil Engineering, University of Manchester, England [17,18]; and the Score-Stove™ project aiming to generate electricity in developing countries using thermo-acoustics powered by burning wood. This project initiated a broad collaboration between the University of Nottingham, University of Manchester, Queen Mary University of London (QMUL), Imperial College London and Los Alamos National Laboratory (LANL) [19–23] ; Recently, a solar-operated thermoacoustic Stirling engine has been reported for the first time to produce as much as 200 W of electrical power with overall efficiency of 12.7% (heat to electricity) at 750 °C [24]. The additional option of heating the engine with solar-thermal energy has led to a compromise of the performance of this prototype compared to earlier versions [8].

Despite its conceptual simplicity and high reliability, nowadays further efficiency improvements are necessary for a complete TASE-based system to gain a market share. Other well-established heat-to-electricity conversion systems have been around for a long time, and competing with them, mainly for efficiency, represents an important challenge for the TASE system.

The main objective of this research has been to provide a qualitative understanding as well as quantitative analysis of the key parameters affecting the complex thermal–acoustical–electrical system. A fairly involved trade-off exists between different parameters affecting the performance of the system. In particular, we address the effect of mechanical friction, known to have a deleterious impact on the system performance. To better understand this effect, an analytical model is developed in this paper. Its results will be compared to a detailed thermoacoustic simulation using DeltaEC™ in a separate paper. An alternative method of measurement for precise determination of the mechanical friction constant was developed and is described.

Section 2 gives a short background of thermo-acoustic-electrical transduction. An analytical model of the involved processes is presented in Section 3. Section 4 describes the experimental setup