Thermoacoustic Electric Generation

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UMR CNRS 6613
Outlines

- Introduction
- Theory
- Some realizations
- Future development
Thermoacoustic Engine

Introduction
Thermo-acousto-mechanical device

- Stack of plates
- Heat exchanger
- Acoustical Resonator
- Mechanical Resonator
- Mechanical work
- Heat source
- Acoustic work

Symbols:
- \( Q_h \)
- \( Q_c \)
- \( w_{ac} \)
Thermo-acousto-mechanico-electrical device

- Heat source
- Acoustic work
- Mechanical work
- Transduction
- Electricity

Symbols:
- $Q_h$
- $Q_c$
- $w_{ac}$
Different architectures

Heat source

\[ Q_h \]

\[ W_{ac} \]

Transduction

Electricity

\[ Q_c \]
Different architectures

Heat source

- Solar dish
- Waste heat
- Biomass
- ....
Different architectures

Introduction

Resonator

Standing wave thermoacoustic engine

- p and v are out of phase + stack

\[ L_{\text{resonator}} \sim \frac{\lambda}{2} \]
Different architectures

Introduction

Resonator

Standing wave thermoacoustic engine

- $p$ and $v$ are out of phase + stack

$\text{L}_{\text{resonator}} \sim \lambda/2$

Travelling wave thermoacoustic engine

- $p$ and $v$ are in phase + regenerator

$\text{L}_{\text{loop}} \sim \lambda$

$\text{L}_{\text{resonator}} \sim \lambda/2$
Different architectures

Introduction

Electro-mechanical transducer
Different architectures

Introduction

Electro-mechanical transducer

Piezoelectric sensors

Piezoelectric Effect
Different architectures

Introduction

Heat source

Transduction

Electricity

Piezoelectric sensors

Electrodynamic sensors

Qdrive's 1S102M/A linear reciprocating motor/alternator
Different architectures

Introduction

Other stuff

- Gaz
- Stack/regenerator material
- Heat exchangers
- ....
Outlines

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- Future development
Theory: engine design

- Case of traveling-wave loop thermoacoustic device

Analytical theory, but practically: **Use of Delta-EC** (or equivalent software)

Feedback loop

- High acoustic impedance at the entrance of the regenerator
  (minimization of viscous losses)

- **P and v in phase**
  (traveling wave condition)

- Thermal to acoustic efficiency

\[ \eta_{ta} = \frac{P_a}{Q_h} \]
Theory: acousto-electric coupling

- Case of a linear alternator, seen as an electrodynamic loudspeaker

Electrical network equivalent to the alternator
Theory: acousto-electric coupling

- Electrical impedance

\[ Z_{el}(\omega) = R_e + j\omega L_e + R_L \]
Theory : acousto-electric coupling

- Electrical impedance

\[ Z_{el}(\omega) = R_e + j\omega L_e + R_L \]

- Mechanical impedance

\[ Z_m(\omega) = R_m + j\omega M_m - j\frac{K_m}{\omega} \]
Theory : acousto-electric coupling

- Electrical impedance

$$Z_{el}(\omega) = R_e + j\omega L_e + R_L$$

- Mechanical impedance

$$Z_m(\omega) = R_m + j\omega M_m - j\frac{K_m}{\omega}$$

- Electrical current flowing through the loading resistor $R_L$

$$I(\omega) = F(\omega) \left[ \frac{Bl}{Z_e(\omega)Z_m(\omega) + Bl^2} \right] = p(\omega) \cdot S \left[ \frac{Bl}{Z_e(\omega)Z_m(\omega) + Bl^2} \right]$$
Theory: acousto-electric coupling

- Electric power dissipated in resistor $R_L$

$$P_e(\omega) = \frac{1}{2} \Re \{ I \cdot U^* \} = \frac{1}{2} |I(\omega)|^2 R_L = \frac{1}{2} |p(\omega)|^2 S^2 R_L \left| \frac{Bl}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right|^2$$

- Input acoustic power

$$P_a = \frac{1}{2} \Re \{ p \cdot w^* \} = \frac{1}{2} \Re \left\{ p \cdot \frac{p^*}{Z_a^*} \right\} = \frac{1}{2} |p|^2 \Re \{ \frac{1}{Z_a} \} = \frac{1}{2} |p(\omega)|^2 S^2 \cdot \Re \left\{ \frac{Z_{el}(\omega)}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right\}$$

$$\eta = \frac{P_e(\omega)}{P_a(\omega)} = \frac{R_L \left| \frac{Bl}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right|^2}{\Re \left\{ \frac{Z_{el}(\omega)}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right\}}$$
Theory : acousto-electric coupling

- Acoustic to electrical efficiency

$$\eta = \frac{P_e(\omega)}{P_a(\omega)} = \frac{R_L \left| \frac{Bl}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right|^2}{\Re \left\{ \frac{Z_{el}(\omega)}{Z_m(\omega) \cdot Z_{el}(\omega) + Bl^2} \right\}}$$

- If $L_e \omega << R_e$, then $R_{el} \approx R_e + R_L$

- If $\omega = \omega_r$, then $Z_m = R_m$

$$\eta = \frac{Bl^2 R_L}{R_m \cdot (R_L + R_e)^2 + Bl^2 \cdot (R_L + R_e)}$$
Thermoelectric coupling

- Thermal to electrical efficiency
  \[ \eta_{\text{te}} = \frac{P_e}{Q_h} \]

- Not so easy to predict from separate study of each part of the device
- Strong coupling between thermoacoustic resonator and alternator

The device has to be designed as a whole
Outlines

- Introduction
- Theory
- Some realizations (non-exhaustive)
- Future development
Standing waves devices

Standing waves devices

Huelsz et al., Magneto-hydro-dynamical transduction, 2006
Standing waves devices

Huelsz et al., Magneto-hydro-dynamical transduction, 2006


Application: Diesel truck waste heat recovery
Standing waves devices

Last development in Energy harvesting
Smoker et al., Nouh et al., 2012 - 2014

- Input heating power : $Q_h = 40$ W
- Output electric power : $P_{el} = 0.12$ mW
- Acoustic to electric efficiency : $\eta_{ae} \approx 10\%$
- Global efficiency : $\eta \approx 3 \times 10^{-4}\%$

Low efficiency, but can be miniaturized and distributed

- **Still in progress...**
Traveling waves devices

S. Backhaus et al., Los Alamos Lab., 2004

- **Fluide**: He, 55 Bar
- **Volume**:
  \[ V_{cavarr} = 0.01 \text{ l} \]
  \[ V_{tot} > 2 \text{ l} \]
- **Performance**:
  \[ f \approx 120 \text{ Hz} \]
  \[ T_h \approx 600 \text{ °C} \]
  \[ Q_h < 400 \text{ W} \]
  \[ Q_{el\text{max}} \approx 58 \text{ W} \]
  \[ \eta_{\text{max}} \approx 18 \% \]
Traveling waves devices

Yu et al., Score project, 2012

Low cost electricity generator for rural area driven by biomass

- Fluid : air, 1 Bar
- Volume:
  - $L \approx 4.25 \text{ m}$, $R = 2.7 \times 6.4 \text{ cm}$
  - $V_{tot} > 10 \text{ l}$
- Performance:
  - $f \approx 70 \text{ Hz}$
  - $T_h \approx 120 \degree C$
  - $Q_h < 500 \text{ W}$
  - $Q_{el_{max}} \approx 11.6 \text{ W}$
  - $\eta_{max} \approx 3 \%$

Classical loudspeaker set in the loop
Traveling waves devices

Hekyom, 2011: Demonstrator of thermoacoustic electricity generator

- $P_{el} = 800 \text{ W}$
- $T_h = 950 \text{ °C}$

2 Q-Drive transducers

Electric feedback loop

- For more information, ask M. X. FRANCOIS
Traveling waves devices

Research Program of China, 2010 – 2014, Sun et al., Wu et al.

Thermoacoustic electric generator coupled to a solar dish

- Fluid: He (95.5%) Ar (4.5%), 40 Bar
- Performance:
  - $f = 64$ Hz
  - $T_h = 650$ °C
  - $P_{el\ max} \approx 1040\ W\ (*)$
  - $\eta_{max} \approx 19.8\%\ (*)$

* In lab conditions
Traveling waves devices

Qnergy, TASE-3 project, 2014

Produces 1 kW of electrical power during solar operation

Qnergy's TASE-3 thermoacoustic Stirling engine during operation at the company's test facility in Ogden, Utah.
Traveling waves devices

Research Program of China, 2014, Wu et al.

3 kW double-acting thermoacoustic Stirling electric generator

- **Fluide :** He 50 Bar
- **Performance :**
  - $f = 86\, \text{Hz}$
  - $T_h = 650\, \text{°C}$
  - $P_{\text{el max}} \approx 1570\, \text{W}$
  - $\eta_{\text{max}} \approx 16.8\%$
Outlines

- Introduction
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- Future development
Future development

Key points

- Heat exchangers
- Alternators
- Thermoacoustic process
Future development

$P_e (W)$

years


Future development
Future development

$P_e (W)$

years


500 1000 1500
Other alternators?

Thermo Acoustic Power Program, ASTER, K. de Block, 2013

- For more information, ask K. de Block
Other alternators?

MHD Electric Generator, A. Alemany et al., 2010

- For more information, see presentation of A. Alemany
Thermoacoustic process optimization

- Control of non-linear effects
  - For example: Acoustic streaming

- For more information, see presentation of H. Bailliet
Thermoacoustic process optimization

- Active tuning of acoustic oscillations in a thermo-acoustic power generator

Work in progress at « Laboratoire d’Acoustique de l’Université du Maine » (LAUM)

Thermoacoustic process optimization

- Active tuning of acoustic oscillations in a thermo-acoustic power generator

- **Thermoacoustic core:**
  - Ambiant heat exchanger
  - Regenerator
  - Hot heat exchanger
  - Thermal buffer tube
  - Ambiant heat exchanger

- **Fluid:** air
- **Static pressure:** 5 Bars
- **Ambient temperature:** 295 K

- **Frequency:** 40 Hz
- **Onset condition:** $Q_h = 60 \text{ W}, \Delta T = 401 \text{ K}$
- **Above onset:** $Q_h = 70 \text{ W}, \text{DR} = 1\%, \eta_\varnothing = 0.24\%, \Delta T_\varnothing = 407.7 \text{ K}$
  - $Q_h = 140 \text{ W}, \text{DR} = 3.2\%, \eta_\varnothing = 0.71\%, \Delta T_\varnothing = 452 \text{ K}$

- **Low efficiency:** engine = study model (modular, limited budget, low efficiency alternator) but designed to work close to its maximum value.
Thermoacoustic process optimization

- Experimental results: case with internal auxiliary source

\[
\eta = \frac{W_{el} (G=0) + \Delta W_{el}}{Q_h + W_{ls}}
\]

- Efficiency \( \eta \) versus \( \phi \) for different \( G \)

\[Q_h = 70 \text{ W}, \ G = 0 (-), 10 (-), 40 (\Diamond), 70 (+), 135 (\Box) \text{ or } 190(\circ), \text{ without active control} (--)\]
Thermoacoustic process optimization

- Efficiency $\eta$ versus $G$ for $\phi = \phi_{\text{optimal}}$

$Q_h = 70 \text{ W (o)}, 100\text{ W (o)},$ without active control (..)

- $\Delta W_{el}$ (o) : additional power produced
- $W_{ls}$ (•) : power supplied to the auxiliary source
Thermoacoustic process optimization

- Active control applied on a high power thermoacoustic compact engine (currently being built at LAUM)

- Fluid: helium
- Static pressure: 22 Bars
- Heat input: 1000 W
- Efficiency (theoretical): 20%
- Electric power: 200 W

- Alternator: Qdrive 1S 132D

Work in progress ...
Thank you for your attention...