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Abstract: A small thermoacoustic-Stirling engine demonstration device that can produce sound in excess of 100 dB at 560 Hz has been constructed. The engine consists of a quarter wavelength acoustic resonator with a smaller diameter coaxial regenerator positioned toward the resonator's closed end, thereby forming an acoustic feedback path around the regenerator. Acoustic oscillations begin spontaneously when the hot heat exchanger adjoining one end of the regenerator is heated to a sufficient temperature. A water stream in a second heat exchanger maintains the opposite end of the regenerator near ambient temperature. This device was inspired by the Backhaus-Swift engine[1] and is a preliminary step in the investigation of regenerator operation at frequencies much higher than may be practical with mechanical or free-piston Stirling engines.

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1. Introduction

Swift, Gardner, and Backhaus have recently developed and built a pistonless thermoacoustic-Stirling refrigerator[2] and engine[1,3] incorporating a regenerator at a location of traveling wave phasing in a lumped element acoustic feedback loop. This approach eliminates the pistons and mechanical linkages typically associated with Stirling engines and represents a great simplification of these heat engines while maintaining high efficiency. The device presented here was inspired by their engine and draws from the work of others.[4,5,6] One of the goals of this work is to demonstrate that a regenerator can function properly in devices that operate around 600 Hz, a frequency five times higher than the highest frequency mechanical Stirling engine or free piston Stirling engine of which we are aware.[7] Another goal is to construct a simple, portable device that can be used as a lecture demonstration.

Thermoacoustic-Stirling engines differ from "conventional" standing-wave thermoacoustic engines[8] in the method by which the working fluid is transported through the thermodynamic cycle. Proper phasing between heat transfer and particle displacement in a standing-wave device is set in part by the stack, a porous matrix that has imperfect thermal contact with the gas passing through it.[9] Its hydraulic radius, a measure of the pore size, is typically set to be close to the thermal penetration depth of the gas, which is the characteristic distance that heat can diffuse in $1/\pi$ times the acoustic period. This imperfect thermal contact results in a time delay in heat transfer between the gas and stack. Hence, locating the stack in an acoustic standing wave causes the gas within the stack to have a specific volume change due to heat transfer from the stack, which is partially in phase with the acoustic pressure, thus doing work that adds energy to the acoustic oscillation. This imperfect thermal contact also results in the heat transfer being partially irreversible, which generates entropy and limits the maximum efficiency of the cycle.

By way of contrast, higher efficiency thermoacoustic-Stirling devices have a porous matrix called a regenerator, which is similar to a stack but with finer spacing so as to be in intimate thermal contact with the gas it contains. The regenerator's hydraulic radius is small compared with the gas's thermal penetration depth, causing a negligible phase lag with nearly ideal, reversible heat transfer and hence higher cycle efficiency. For the expansion of the gas due to heat transfer to have a component in phase with the acoustic pressure, so as to add energy to

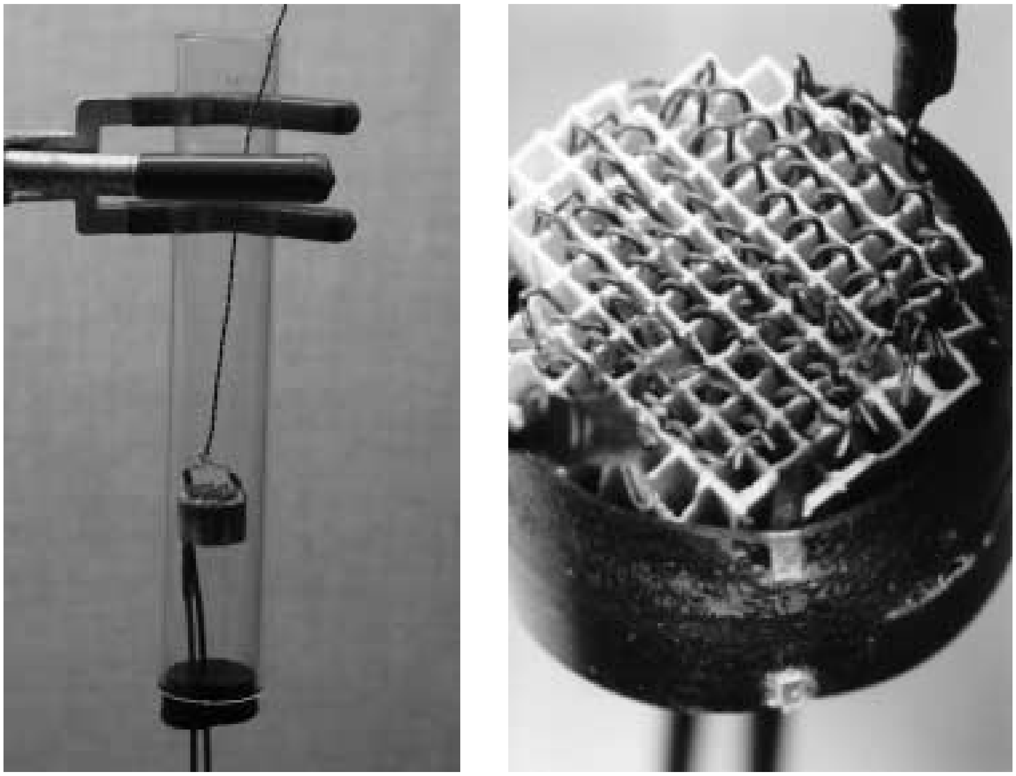

Fig. 1. The thermoacoustic-Stirling heat engine demonstration device and a closeup of the regenerator assembly emphasizing the hot heat exchanger construction.

the acoustic oscillation, the acoustic pressure and volume velocity at the regenerator should be in phase.[1,10] This phase relationship is established by a lumped element acoustic mass-spring feedback network[1] at the end of the standing wave resonator.

As pictured in Fig.1, this thermoacoustic-Stirling engine consists of a quarter wavelength standing wave resonator, with a regenerator flanked by heat exchangers suspended a short distance from the closed end. The lumped element acoustic mass-spring feedback network is formed by locating a small diameter regenerator in a larger diameter resonator tube. The annular space between the resonator wall and the regenerator acts as a lumped acoustic mass. The space between the regenerator and closed end of the resonator acts as a gas spring. This mass-spring sub-system is tuned to have a resonant frequency well above the operating frequency. This results in the pressure oscillations at the closed end of the resonator being slightly resonantly enhanced in magnitude with respect to the driving point at the upper end of the regenerator, and negligibly shifted in phase. Thus, the acoustic pressure on opposite sides of the regenerator is nearly in phase, but the amplitude is slightly higher on the lower, cold side than on the upper, hot side. Therefore, during the half of the acoustic cycle when the pressure on both the hot and cold sides swings positive, there is a small pressure gradient across the regenerator that drives the gas inside from colder to hotter locations. This gas velocity is in phase with the pressure gradient, which, in turn, is in phase with the pressure swings on either side of the regenerator, yielding traveling wave phasing at the regenerator even though the phasing elsewhere in the device is primarily that of a standing wave.

The gas in the regenerator expands during the positive half of the acoustic cycle as it moves towards the hot side of the regenerator, increasing the positive pressure even more than it would have otherwise been in absence of the temperature gradient, doing work on the rest of the gas in the resonator. During the other half of the cycle, the pressures at the hot and cold sides swing negative, with a slightly larger swing on the cold side. This causes a gradient that drives the gas in the regenerator to move toward the cold side, where it cools and contracts, thereby causing the pressure to swing even further negative. As in standing-wave prime movers, given a sufficient temperature difference between hot and cold exchangers, any small pressure fluctuation at the resonant frequency of the device will grow in amplitude, filling the device with sound.

2. Design and Performance

The resonator of the thermoacoustic-Stirling engine is a 15 cm long Pyrex tube with a 21.5 mm inner diameter. One end is open to permit sound radiation; therefore, the engine's working fluid is atmospheric pressure air. The 3.4 mm long regenerator is made of twenty-eight 16 mm diameter, 200 mesh stainless steel screens (having wires of diameter 0.041 mm, spaced 0.086 mm apart). The hydraulic radius of the regenerator is 0.05 mm, as compared to the thermal penetration depth of 0.11 mm in 20 °C air, or 0.22 mm in 350 °C air. The regenerator screens are held between two heat exchangers in a stainless steel sleeve of wall thickness 0.025 mm. The cold/ambient heat exchanger, located at the bottom of the regenerator, is a single layer of 24 mesh copper screen (having wires of diameter 0.36 mm, spaced 0.71 mm apart) with a 1.6 mm o.d. copper tube soldered around its circumference. Through this tube, 20 °C water circulates to hold the end of the regenerator near ambient temperature. The tube extends through the rubber stopper that forms the closed end of the resonator, hence it also functions to position the regenerator assembly within the resonator. The hot heat exchanger, consisting of a 0.5 m length of 0.25 mm diameter nickel-chromium heater wire, is located on the upper end of the regenerator. The wire was corrugated into a zig-zag shape. To prevent electrical shorting, the tips of these wire "loops" were individually inserted into the square pores of a ceramic honeycomb matrix,[11] where they are held in place by friction. The tips of the heater wire are visible in Fig.1, extending above the end of the 3.5 mm long ceramic fixture, which was made as short as possible because any extra surface area detrimentally adds thermoviscous power loss. The thermoacoustic modeling software DeltaE[12] was used as an aid in optimizing the dimensions of the engine.

Ten seconds after 1.8 amps (30 watts) of alternating current is applied to the hot heat exchanger's nickel-chromium wire, a sufficient temperature gradient is set up across the regenerator so that the device emits an intense (100 dB *re* 20 μPa at 1 m) tone. The frequency of oscillation is set by the length of the standing wave resonator. With a 15 cm long resonator, the engine emits a 560 Hz tone. Placing the same regenerator assembly in a 9 cm long resonator causes it to emit a less intense 850 Hz tone, because the device is optimized to operate at 560 Hz.

The engine's actual performance was compared to the DeltaE model's predicted performance to ensure adequate understanding of the engine's behavior. At a different operating point, the pressure at the closed end of the tube was measured with an Endevco[13] microphone to be 3540 Pa. Given this value and the geometry of the engine, the DeltaE model predicts the particle velocity at the resonator's opening to be 9.0 m/s, and the required hot-side regenerator temperature to be 350 °C. Given this particle velocity, the radiated acoustic pressure[14] at 1 meter should be 92 dB *re* 20 μPa. The pressure at this location was experimentally measured to be 94 dB, and the regenerator's hot side temperature was measured with a thermocouple to be 390 °C.

Although these temperatures and pressures are in reasonable agreement, it was necessary to apply 4 or 5 times the amount of heat to the hot exchanger than was predicted by the DeltaE model. There are many possible heat loss mechanisms that were not accounted for in the model. Gedeon streaming,[1,2,15] a time-averaged mass flow associated with acoustic work flow, could have been transporting heated gas from the hot heat exchanger through the annular space to the ambient exchanger. Several techniques have been developed to counter this loss mechanism,[1,2,5] but none were used in this device. Further, Rayleigh streaming,[1] ordinary convection, gas thermal conduction, or IR radiation could have transported heat away from the exchanger and out of the resonator. Extending the stainless steel sleeve 10 mm vertically past the hot heat exchanger, insulating its walls, and placing a second ambient heat exchanger at the upper end of this lengthened sleeve could have minimized this extraneous heat loss. These new components would be equivalent to the thermal buffer tube and secondary heat exchanger used by Backhaus and Swift[1] for this same purpose. However, to simplify the demonstration device, none of these parts were incorporated.

The addition of a thermal buffer tube and second ambient heat exchanger might also prevent the nonsteady state behavior of this engine. Over a period of approximately one minute after onset, the amplitude of sound radiated from the demonstration device slowly decreases to zero. Because the gas in the feedback path is heated due to its direct exposure to the nearby hot heat exchanger, the desired traveling wave phasing at the location of the regenerator is disturbed. In addition, gas in the resonator is heated as well, increasing the resonance frequency, further decreasing the efficiency of the engine.

The use of atmospheric pressure air in this demonstration device results in a lower areal power density than typical Stirling devices, which use pressurized helium. However, the high operating frequency we have shown here and the concomitantly shorter resonator length could allow comparable volumetric power densities, resulting in compact, practical thermoacoustic-Stirling devices.

Acknowledgment

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