Figure of merit for regenerator working in acoustic field

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To specify the performance of a TA device, the quantitative description of regenerator is a significant problem in determining the performance of the whole TA system. More attention should be paid on this problem since thermoacoustic system tends to work in high frequency and high amplitude acoustic field, and complexity caused by the last two factors has not been revealed. Aiming to the mentioned problem, a series of experimental and theoretical investigation works have been carried on by the reporter's group.

BACKGROUND

Regenerator is not merely a heat exchanger in the system with pressure oscillation, now this view point has been recognized commonly. To specify the performance of a TA device (including regenerator and stack, we'll call it regenerator later on in this article), quantitative description of regenerator in determining the performance of the whole TA system is a significant problem. Most of the information about regenerator has been obtained only by analysis or computation on simulated models, few of them has been verified or supported by experiments. More attention should be paid on this problem since thermoacoustic system tends to work in high frequency and high amplitude acoustic field, and the complexity caused by the last two factors has not been revealed..

Aiming to the mentioned problem, a series of experimental and theoretical investigation works has been carried on by the reporter's group [3-8].

EXPERIMENTAL INVESTIGATION ON THE RESONANT MODE OF THE REGENERATE IN A STIRLING CRYOCOOLER SYSTEM

After successful modeling of pressure wave propagation in an isothermal regenerator by a passive network of fluid flow reactance [3], recently the thermoacoutic conversion in a regenerator has been characterized by an active network made up of acoustic impedance and a source element reflecting the contribution of gas parcel velocity variation during its reciprocating displacement along the longitudinal temperature gradient (see Figure 1) [6].

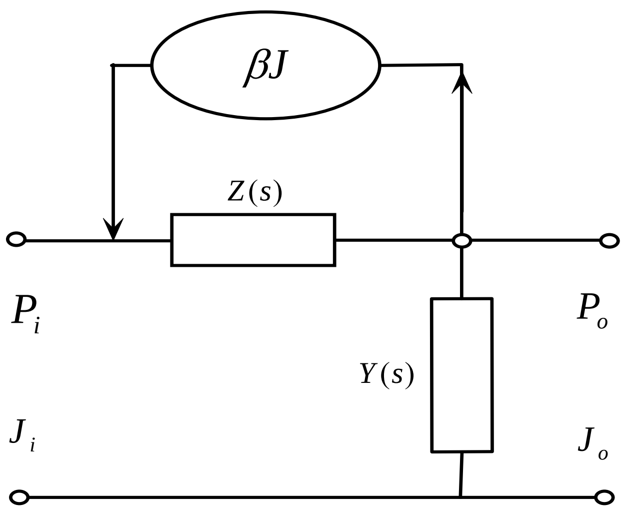

Figure 1 Network modeling for regenerator active network for regenerator with imposed temperature gradient

An experimental split Stirling cryocooler with a controllable displacer (driven by a linear motor) and an adjustable longitudinal temperature difference ΔT_r exerted between the ends of the regenerator has been built to verify this modeling [7].

The longitudinal temperature difference ΔT_r imposes a significant influence on the pressure wave propagation induced by the motion of the displacer in the regenerator. The experimental result revealed that at zero ΔT_r, P_e has a phase lead over P_w of ≈180º (shown in Figure 2), and the amplitude of P_e is very small compared to P_w. With the appearance of ΔT_r, the phase leading to about 90º even if the ΔT_r is small (shown in Figure 2). When the temperature difference ΔT_r attains the level of 120K, the phase of P_w shifts abruptly and comes into phase with P_e. This abrupt phase change reminded the appearance of some resonance effect in the system.

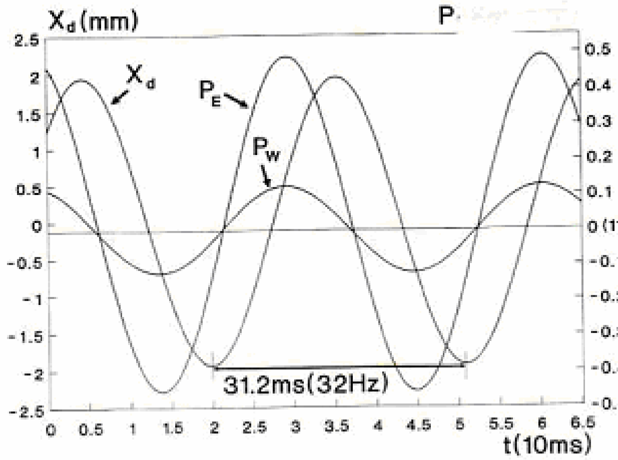

Figure 2 Results of X_d, P_e and P_w oscillation measured at ΔT_r=163K ($T_e = 122K$, $T_w = 255K$)

To explain the revealed resonance effect, a parity simulation circuit of regenerator basing on the network modeling approach, published firstly in [6], has been built. The simulation circuit modeled the regenerator by a coupled LC resonator and the imposed temperature difference to the regenerator by a parallel connected potentiometer which acts as the direct current power source of this circuit (seen in Figure 3).

The imposed ΔT_r cause the periodic variation of density (i.e. impedance L) as shown in Figure4(a) and 4(b),there is an increment of inductance ΔL for each cycle, which converts the heat energy transferred by gas-solid interface into kinetic energy carried by ΔL,thus a parameter called modulation factor can be used to quantify $m = \Delta L / L$,which can be identified directly by dynamical data treatment shown in figure.5. This circuit simulates the modulation and amplification by an analogy between the thermoacoustic and the electro-magnetic wave modulation and amplification process. The simulation circuit has successfully demonstrated that, a resonance mode actually happened at some critical temperature difference. Along with the establishment of a temperature gradient the inductance impedance of regenerator raises because of density increasing, this causes the flow impedance of regenerator varying gradually from the capacitance dominated state to resonant state, which is a resistance dominated state.

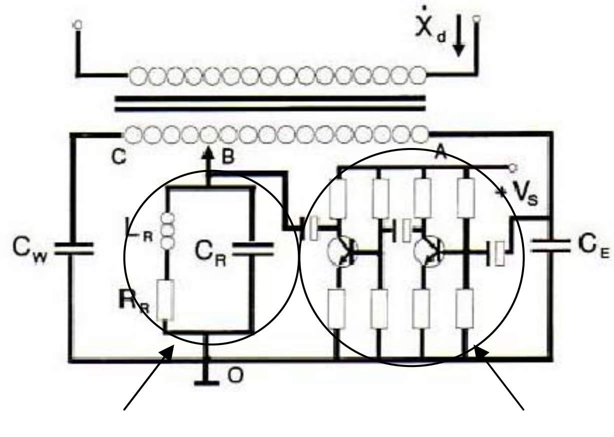

Figure 3 Parity simulation network for regenerator with imposedtemperature gradient

REGENERATOR-RESONANCE CONVERTER WITH HIGH FREQUENCY SELECTIVITY

The network simulating in the circuit shown in Figure3 reminds a widely usable electronic device in electronic communication technique, i.e. the mean frequency active filter. The figure shows the circuit

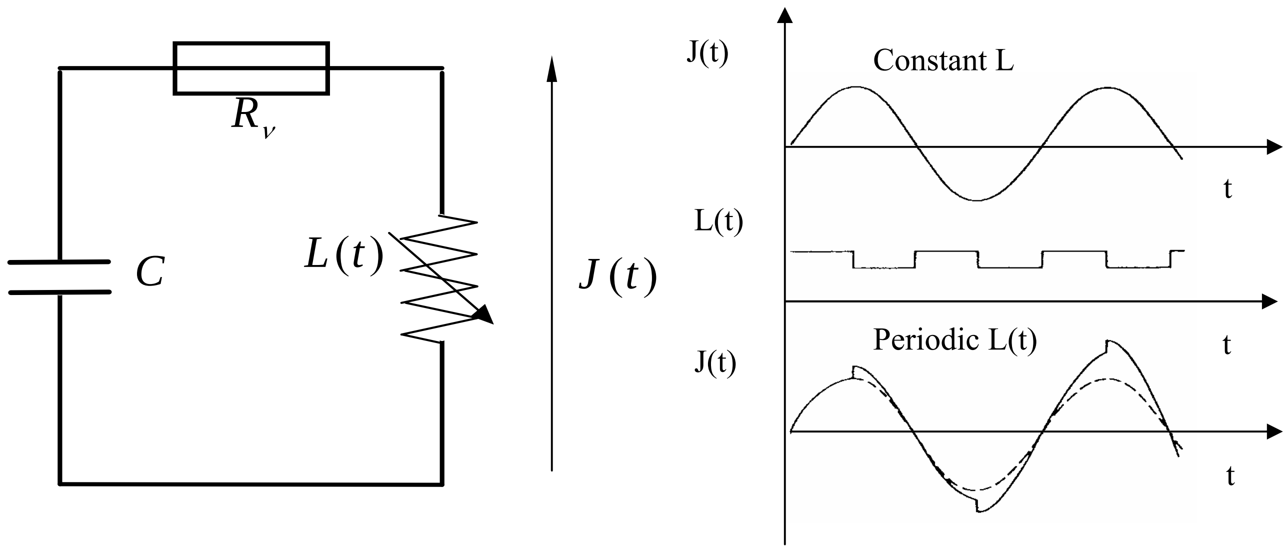

Figure 4 (a) Regenerator—LC coupled converter; (b) Periodic L (t)

coupling a transistor amplifier with a resonance LC circuit, the resonance frequency of it is ω_0 with quality factor of Q.

The regenerator in a TA system plays the same role as the active filter in the above mentioned electronic system. This means that the response of regenerator would have a strong frequency dependence, which has been demonstrated and verified by our experiments in [8] (shown in Figure 6). As shown in these figures, evident peaks of response altitude confirm the existence of optimal frequency for each type of matrix. By network modeling consideration, in an active narrow band amplifier there must be an optimal matching between the frequency spectrum of response given by the transistor amplifier and the connected LC circuit chain. In the regenerator of a thermoacoustic system, the material properties of solid matrix determines the broad band frequency spectrum of transversal entropic wave, while the gas parcels

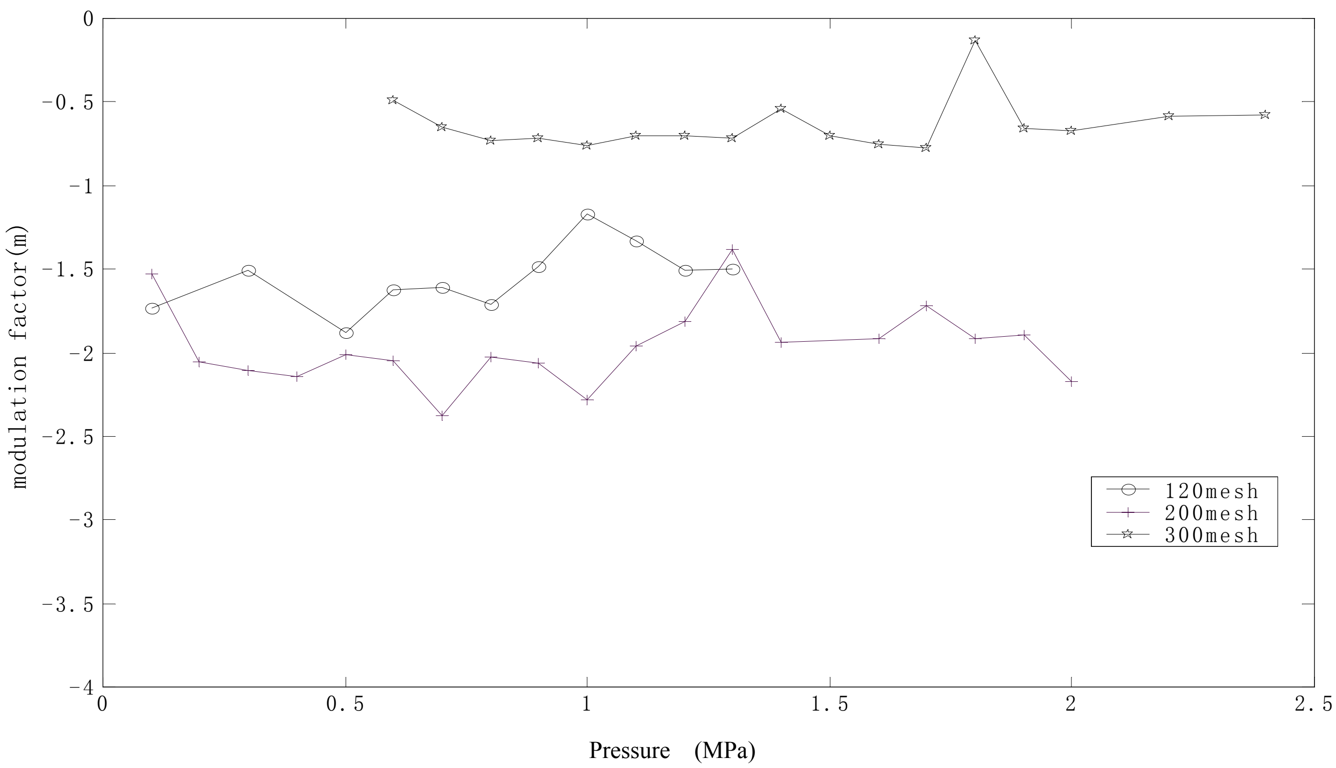

Figure 5 Identification result of modulation factor of different regenerator matrix

carried by the axially propagating acoustic wave play the role of modulator oscillating in a narrow fixed frequency band.

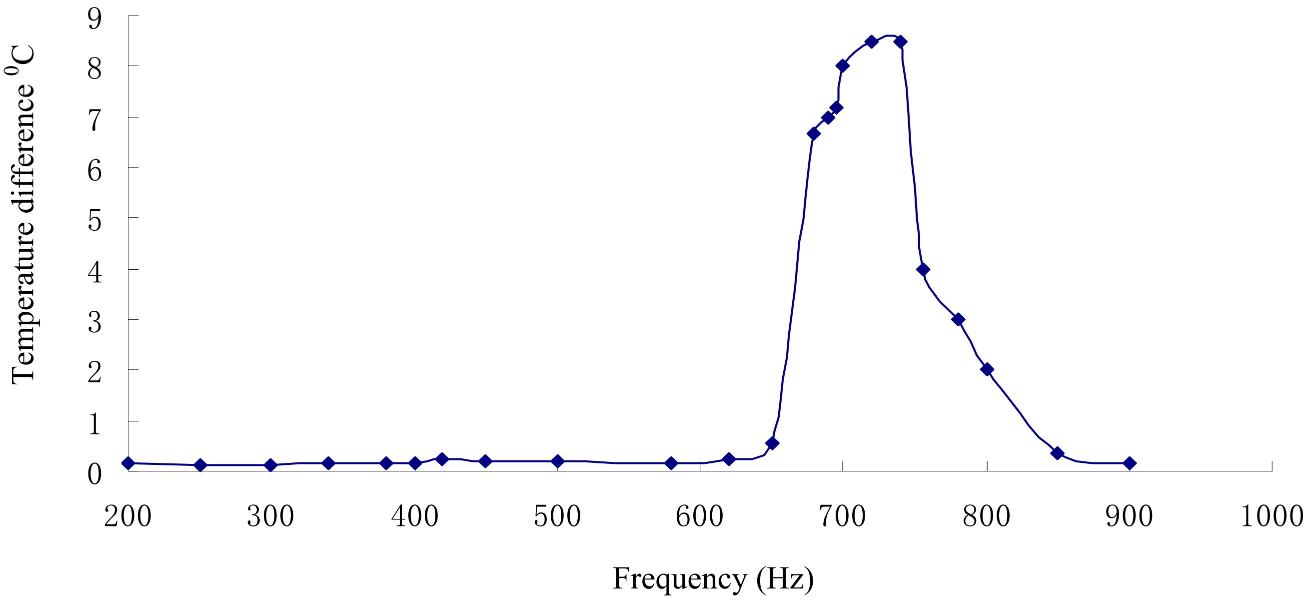

Figure 6 Experiment on the optimal frequency of matrix

THE RESONANCE MODE OF REGENEARTOR IN HEAT DRIVEN THERMOACOUSTIC RESONANCE TUBE

Thus, the recent widely-used active network model of regenerator is only an over simplified description of this nonlinear device, working in a state far from thermodynamic equilibrium especially in the case of heat driven high frequency acoustic field. The heat dynamics of a real high frequency regenerator should take the frequency dependence of its response as one of most important problems. In high frequency application in order to match the entropic wave frequency spectrum of matrix with its LC resonance characteristic, a three frequency parameter network is proposed here to describe our approach to the problem, see figure 7. Initially, the input (left) side in Figure7 is in the state of thermodynamic equilibrium, which is in fact a wide broad acoustic field cause by thermodynamic fluctuation of state. The field can be described by mode density [s/cm^3], which is the acoustic energy ρ_m emitted by unit volume of working substance in unit interval of frequency band, i.e. the number of freedom in unit volume. The input mode ω_i that lies most closely to the intrinsic frequency ω_0 of the TA system with regenerator is the most favorite one to be amplified by the gas parcel displacement modulation in regenerator, while the modulated mode by the imposed temperature gradient is also a small part of gas in the system and is shown in the right side of Figure 7, which includes the oscillating mode with frequency ω_p.

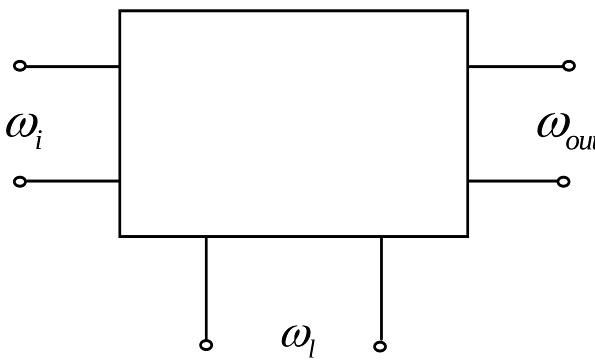

Figure 7 3-frequency parameter network modeling for regenerator in a heat-driven resonance tube

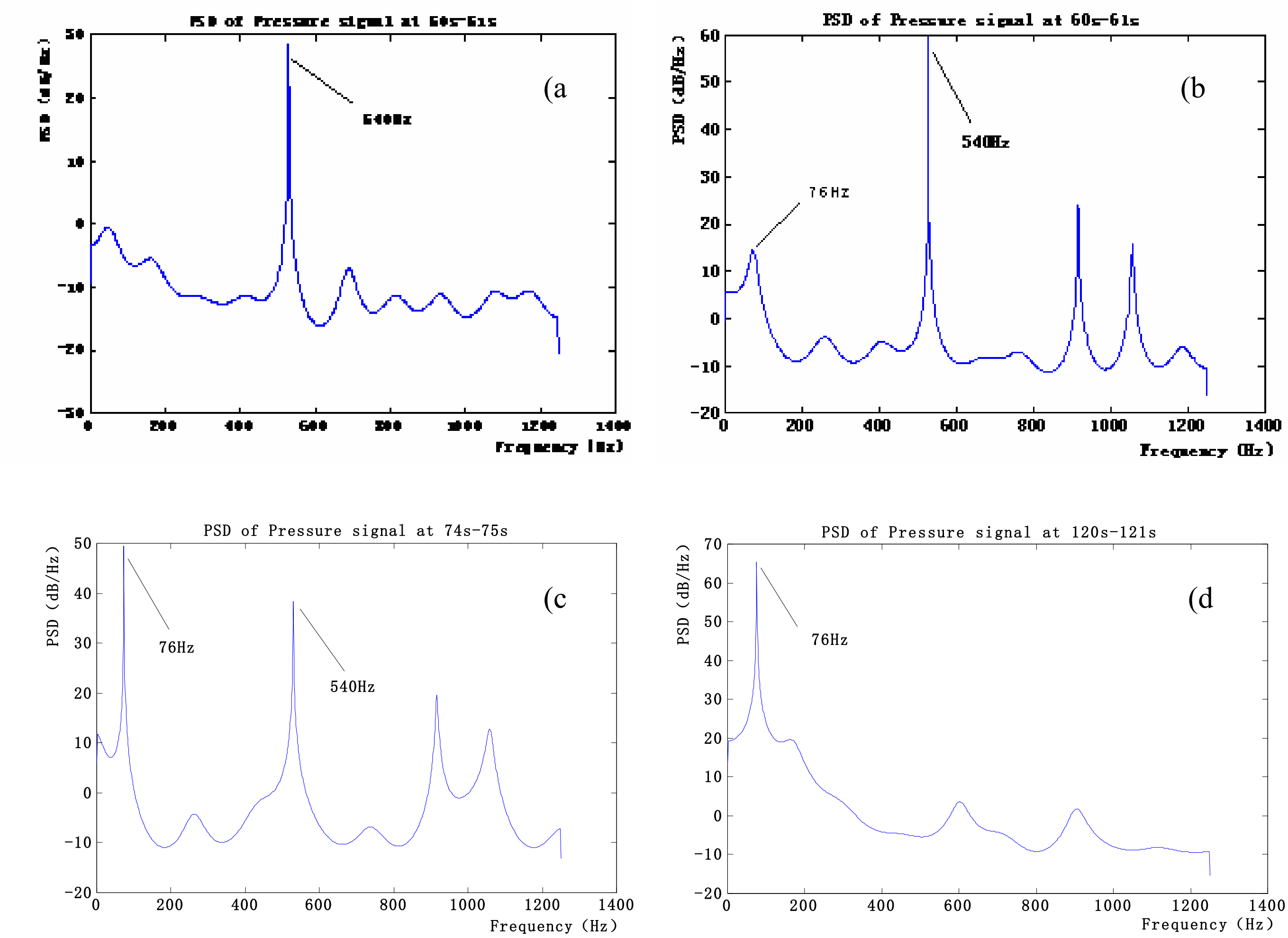

Figure 8 PSD of pressure signal

The connection of regenerator with the LC resonance device shown in figure 3 uses the frequency selectivity feature of the device to provide a narrow band high quality (i.e. high Q) amplifier. The right side of Figure7 shows that among the entropic waves modulated and emitted by the matrix of regenerator only mode with ω_P can be resonated by ω_i according to the rule of parametric resonance

$$\omega_p = n\omega_i \ , \ n = 1, \ 2\cdots\cdots \tag{1}$$

The resonance between ω_p and ω_i results in an oscillation mode of ω_l in the so-called idler loop of the system. To verify the above mentioned model, a heat driven resonance tube has been tested with an intrinsic frequency of 1100Hz. The time series shown in Figure8 demonstrates the filtering process of the resonance tube, resulting in the appearance of resonance only after 170 seconds of heating. This reveals that the matching between the frequency response of regenerator matrix and resonance tube system may be a way for higher thermoacoustic conversion efficiency.

CONCLUDING WORDS

By following the approach of network modeling, works on the better matching between regenerator and its thermoacoustic heat engine system has been carried on. The view point of considering regenerator as an active amplifier with high frequency selectivity and the resonance mode of regenerator may perhaps be an approach to improve the conversion efficiency of a thermoacoustic heat engine system.

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