INDIVIDUAL DEFERENCE OF ULTRASONIC TRANSDUCERS FOR PARAMETRIC ARRAY LOUDSPEAKER

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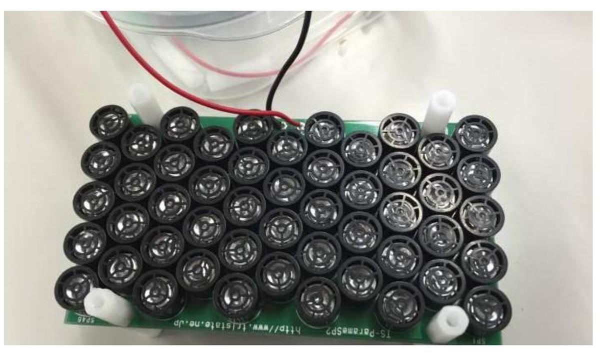
Introduction

- Parametric array loudspeaker (PAL)
  - Yoneyama applied for a loudspeaker in 1983.
  - Radiating ultrasonic modulated by audible sound makes the audible sound with sharp directivity because of nonlinearity of air.
  - Practical Usage: At the audio guidance in museums.
- The component of PAL: Ultrasonic transducers
  - Many transducers are connected in parallel and placed as an array for radiating larger sound pressure of ultrasonic.



- Tasks: **Individual difference of each transducer**
  - **Resonant frequency**
  - Frequency response of radiated sound pressure etc.
    →Necessity of considering the effect to the PAL's audible sound by the difference.
- Making two PAL's arrays with large/small variance of resonant frequencies of transducers.
  - Measurement of the admittance of arrays.
  - Measurement of the radiated ultrasonic and PAL's audible sound.

Theory

- Finite-Amplitude Sound Wave: The sound wave which is too large to ignore nonlinearity
- Radiating finite-amplitude sounds with nearby frequencies.
  - Interaction: the sum / difference frequency sounds are made.

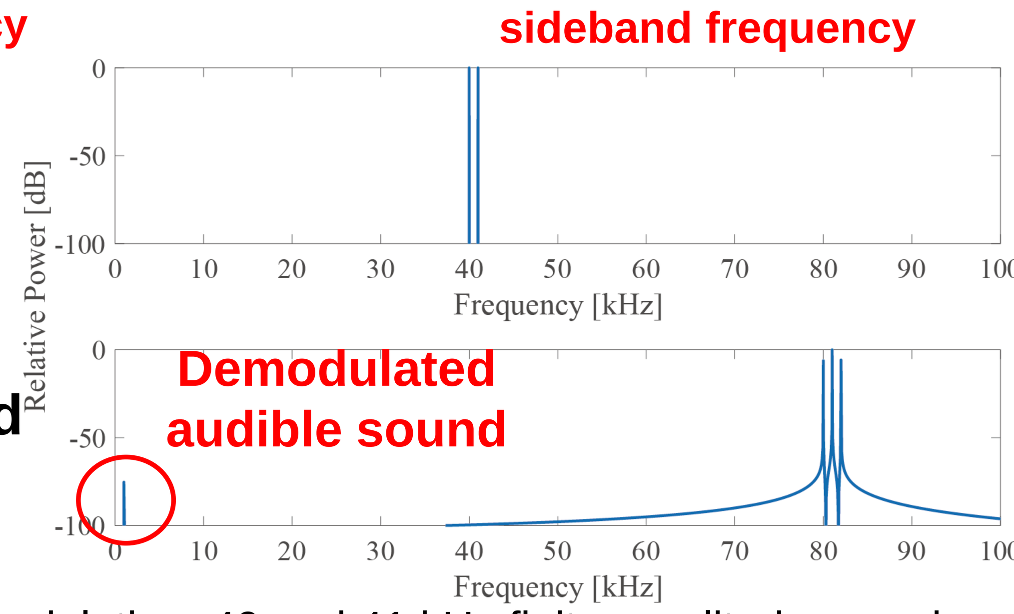
$$p_s(t) = \frac{\beta S}{16\pi\rho_0 c_0^4 \alpha z}\frac{\partial^2}{\partial t^2}p_i(t)^2 \propto \frac{\partial^2}{\partial t^2}p_i(t)^2$$

p_i : sound pressure before interaction S : Area of the speaker
p_s : sound pressure after interaction α : absorption coefficient
β : nonlinearity coefficient z : distance from speaker

  - The difference frequency becomes the audible sound.
- PAL: Ultrasonic modulated by audible sound is radiated.
  - The audible sound generation by the interaction: **Demodulation**
  - The "demodulated" audible sound has sharp directivity.
  - Amplitude of the "demodulated" sound is proportional to the multiplication of these two sounds.

$$P_s(f) \propto f^2 \times \underbrace{P_i(f_0)}_{\text{Sound pressure of carrier frequency}} \times \underbrace{P_i(f_0 \pm f)}_{\text{Sound pressure of sideband frequency}}$$

f : Frequency of the audible sound
f_0 : The carrier frequency of modulated sound



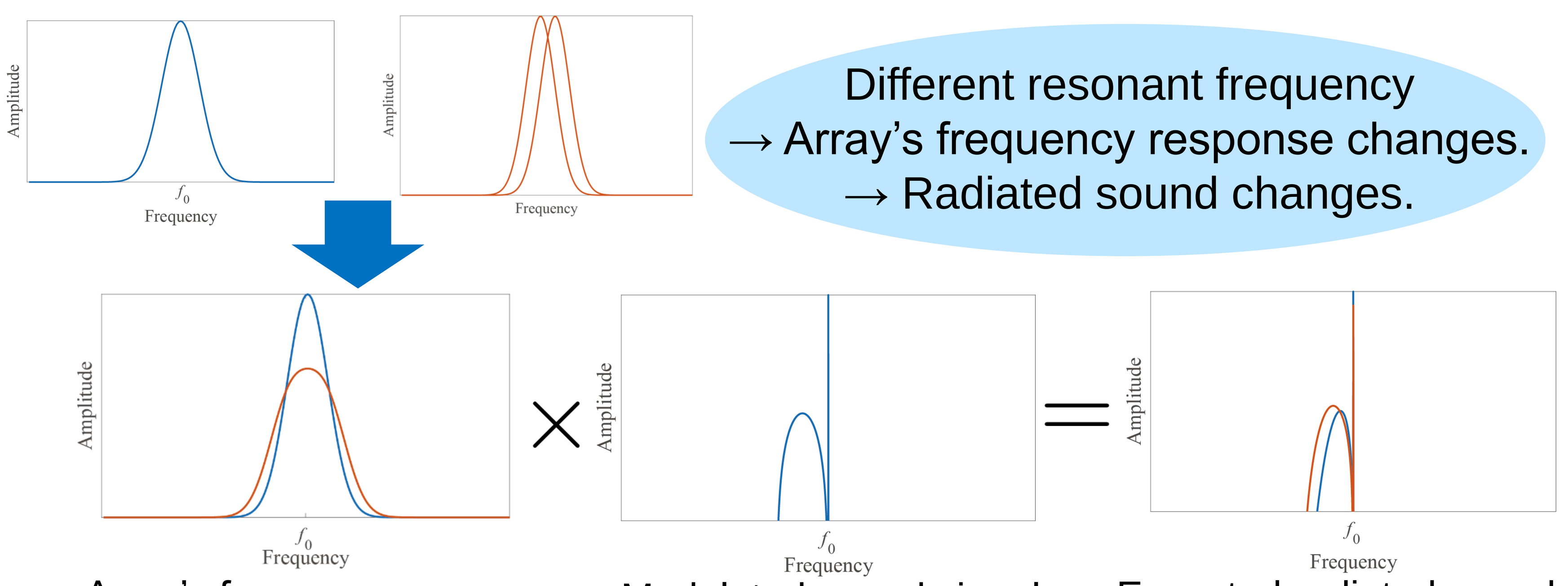
Example of demodulation: 40 and 41 kHz finite-amplitude sound waves make the different 1 kHz sound wave by the interaction.

Influence of Arrangement

- Transducers are placed as an array for making large sound pressure and narrow beam.
  - Using resonant frequency as a carrier of modulation.
    - Focusing on the effectivity of electro-acoustic transformation.
- The radiated sound is determined by input sound and array's frequency response.
  - Array's frequency response: The admittance of an array $Y(f)$ is calculated using n-th transducer's admittance $Y_n(f)$.

$$Y(f) = \sum_{n=1}^{N} Y_n(f)$$

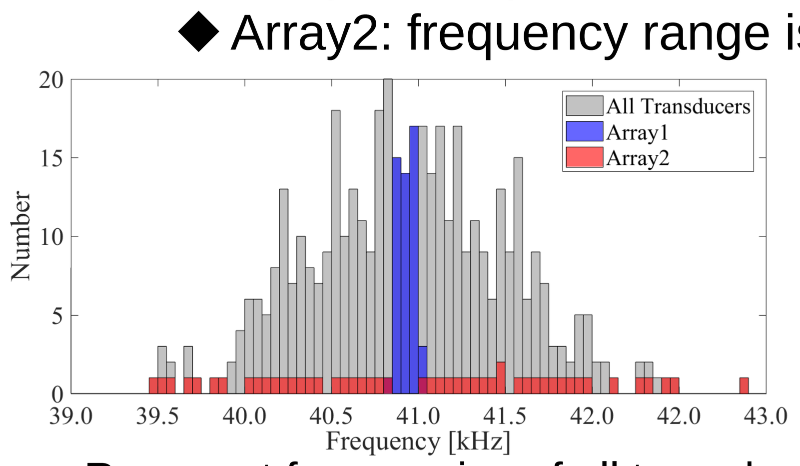
  - The radiated sound: Input sound is filtered by the array.
- Considering the radiated sound influenced by the array is important.
  - Necessity to verify the effect of the difference of transducers.



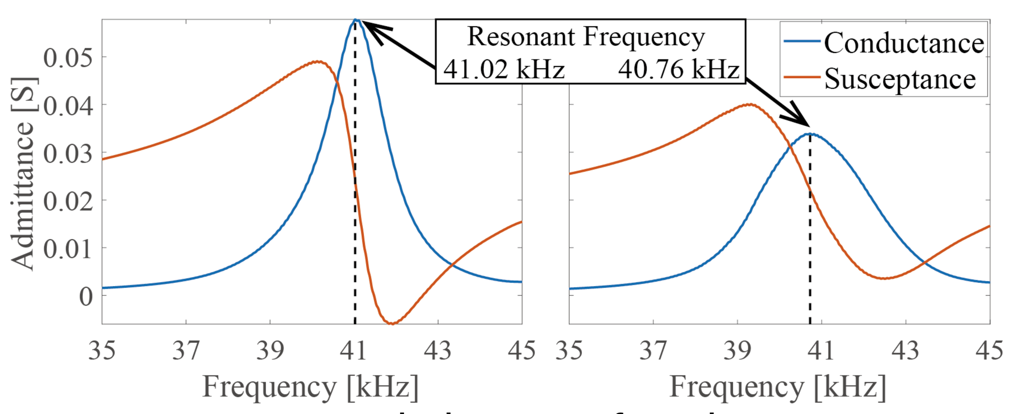
Signal change due to the difference of the resonant frequency.
An array of two transducers whose resonant frequencies are exactly same(Blue lines) and whose resonant frequencies are little different(Red lines) are placed.

Experiment

1. Making array
   - Two arrays which consist of 50 transducers are compared.
   - Transducers with small/large variance of resonant frequency (Array1/Array2).
   - Measurement of the admittance of each array.
     - Array1: sharp resonance is confirmed.
     - Array2: frequency range is wider.



Resonant frequencies of all transducers

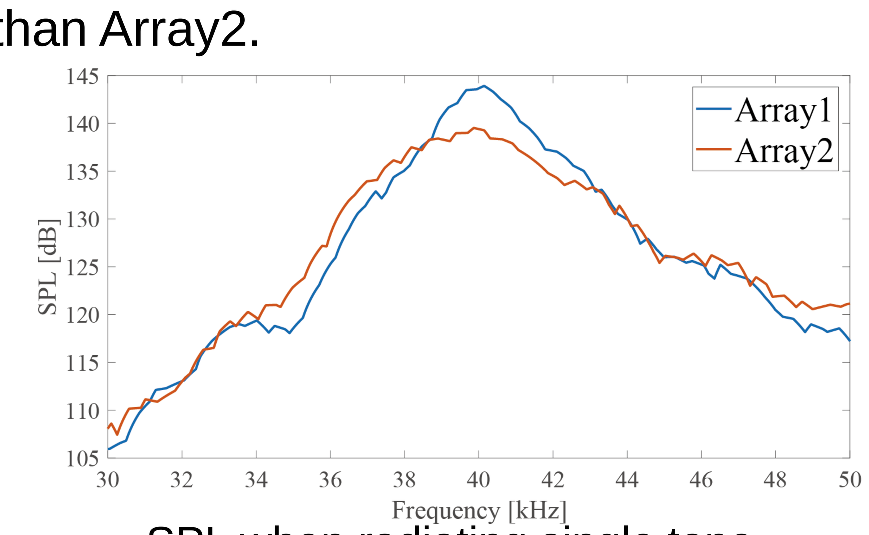


Admittance of each array.

2. Acoustical frequency response
   - Measurement of the sound pressure level(SPL) of ultrasonic when radiating single tone.
   - Array1 can make larger ultrasound than Array2.

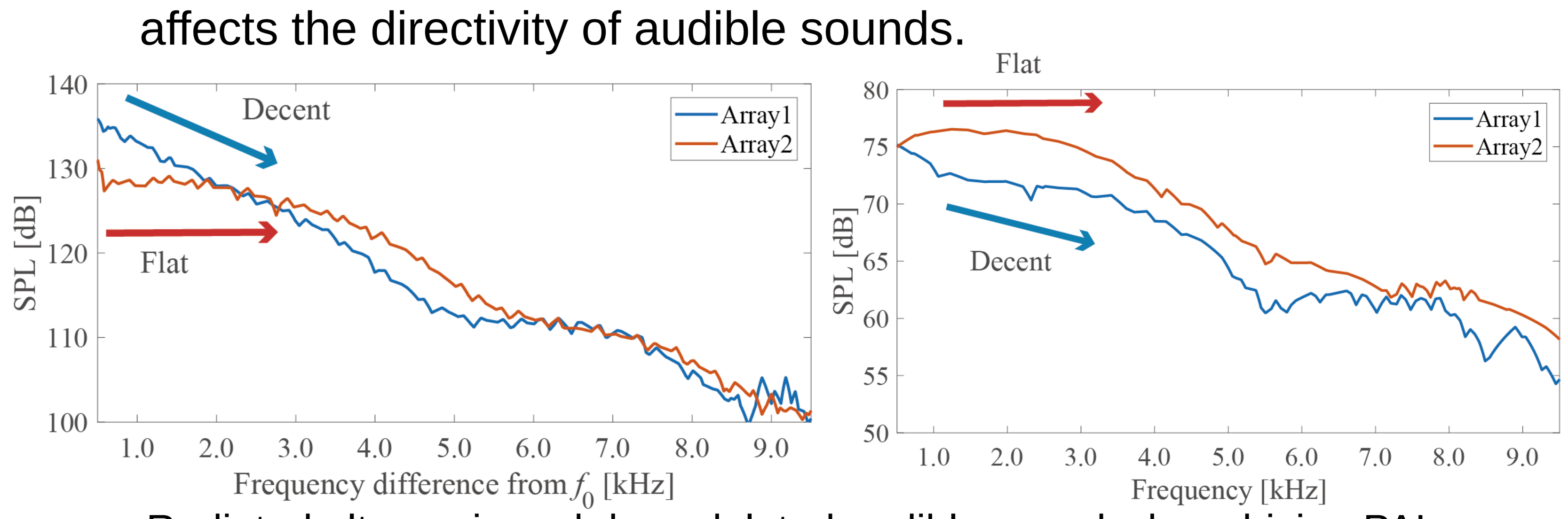
Table Experiment conditions

Item	Value
Radiated signal (in single tone measurement)	30~50 kHz chirp signal
Voltage[Vrms]	10
Mic (ultrasonic)	B&K 4939-A-011
Mic (audible sound)	RION NL-32 Sound Level Meter
Distance [cm]	30



SPL when radiating single tone.

3. Driving PAL: Measurement of SPL of radiated ultrasonic and demodulated audible sound
   - LSB modulation: $S_{\mathrm{LSB}} = Re\left[\left(s(t) + i\mathcal{H}s(t)\right)\exp\left(-i\omega_0 t\right)\right]$ is used and $s(t)$ is 0~10 kHz chirp signal.
   - Radiated ultrasonic: In almost 0~3 kHz from f_0 Array2 has flat frequency response.
     - It corresponds to the result of admittance measurement.
     - In higher than 3 kHz from f_0, both arrays are not flat.
   - Audible SPL is flat to about 3 kHz in Array2, while in Array1 audible SPL declines as the frequency rises.
     - In almost all audible frequency measured, Array2 has larger audible SPL than Array1.
     - Demodulation at neighborhood of array should be concerned?
   - Directivity cannot be measured in detail.
     - It is not measured yet that the difference of array's transducers affects the directivity of audible sounds.



Radiated ultrasonic and demodulated audible sound when driving PAL.
(f_0 is the resonant frequency of PAL array.)

Conclusion

- In order to obtain flat frequency responses of audible sound, an array which has a large variance of the resonant frequency is better suited.
- Verification of influence due to the difference of resonant frequencies of transducers used in array when driving PAL is unsolved.
- Future works: Considering the placement of transducers, and measuring the influences to the initial demodulated sound.