Proceedings of the Internoise 2018/ASME NCAD Meeting
NCAD2018
August 26-29, 2018, Chicago, Illinois, USA

NCAD2018-6111

SOUND ABSORPTION CHARACTERISTIC OF GLASS AND PLASTIC BOTTLES - CONSIDERATIONS OF THEIR DEPENDENCES ON MATERIAL PROPERTIES

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ABSTRACT

Great number of bottles made by glass, plastic and metal are used to store beverages, liquid ingredients as water, milk, vinegar and also liqueur. Empty bottles after usage are collected for recycling use and resources. Many of them have narrow open mouth and look like typical shape in kinds of Helmholtz resonator. Authors thought that their reuse for functional building parts with sound absorption would be very valuable from points of view of green building and environmental policies, and authors then measured each resonance frequency and sound absorption coefficient of representative, including light-soft-plastic, bottles, with net capacity from 7 to 2000 *ml*, by setting on the edge of sound tube with diameter of 100 mm.

Sound resonances with sound absorption coefficient of 0.3-1.0 at frequencies from 100 to 1000 Hz clearly depending on the capacity could be confirmed. It was also found that measured result was well matched to the numerical calculation based on acoustic impedance change at each section area gradually changed in bottle. It is thought that combination use of recycled bottles with independent resonance frequency is more effective than use of new uniform perforated plates for wide space where we need additional sound absorption in certain frequency range.

INTRODUCTION

Large vessels had been discovered around the seat areas of outdoor theater ruins of the Greece-Roman times(1), and illustration of vessels built in the wall of old European stone church can be seen in text books of architectural acoustics with explain on such historical building custom for storing and absorbing sound energy based on the mechanism of Helmholtz resonator(2). One of the authors had been interested in such legend stories and in actual acoustical effects by vessels built in outdoor theaters or reverberant spaces, and then had research work on the effect of a big pair of chinaware's under the stage of Japanese classical drama of "NOH". After the experience of the research work, authors were interesting in sound resonance phenomena, resonators and their sound absorption, and then actually made research works on many kinds of building material including perforated plate(3,4) and resonances in clacks(5) and other applications(6,7,8). Now day, secondary expecting for acoustic effect by such vessels in old time idea already has been lost, because many excellent sound absorptive materials had been developed(9).

However, great number of bottles made by glass, plastic or metal are used for storing liquid materials, and used empty bottles, changed to garbage or recycling resources, are overflowed in our environments. Many of them have thin and long open mouth part like a neck and thick swelled body. From the eyes of authors interesting in acoustical materials, it could be seen that they would be very valuable resources with acoustical function of Helmholtz resonator(2), so authors then researched their actual sound absorption characteristics and differences among various kinds of bottle with large or small size and with different forming materials. Authors could confirm clear sound resonances, sound absorptions and their very simple dependences on the net capacity of bottle.

Authors introduce researched valuable sound absorptive characteristics of many empty bottles in this paper. And also our trials, based on the measurement experiments and numerical simulations with confirming tests to make their acoustical values increasing, are introduced.

NOMENCLATURE

S cross-sectional area of each part of backing air space, neck or open mouth of resonator or sample test bottle.
V volume of the backing air space of the resonator.
c sound velocity in air
c_{no_baf} correction constant for state of without baffle around opening due to decreasing efficiency of in-out flow of sound.
f_r resonance frequency of resonator
j index number for ideal j-th air layer in the test sample bottle from bottom to opening.
l_e effective neck length of resonator
n ideal numbers of test sample sets in unit evaluation area including decimal number less than 1.
t thickness of the ideal air layer
x acoustic resistance at resonance frequency.
z acoustic impedance at surface of air layer or open mouth of sample bottle.
z_c characteristic acoustic impedance of media or air layer.
Δr additional acoustic resistance at the part with narrow section area as neck or open mouth of bottle.
α measured or calculated sound absorption coefficient of test sample(s) of resonator or bottle(s) set in sound tube.
β acoustic admittance as inverse value of impedance.
β_{res} acoustic admittance correspond to sound absorption characteristics of resonator.
β_{vib} ideal acoustic admittance correspond to excited characteristic vibration on the body surface of test sample.
γ complex sound propagation constant in media.

TEST MEASUREMENTS OF SOUND ABSORPTION CHARACTERISTIC OF BOTTLES

Out line of measurement method.

At first, confirming experiments on sound resonance of glass and plastic bottles were done by using the same sound tube method used in past researches on acoustical property of perforated plate(3,4). As shown in "Figure 1.", test sample of bottle was tightly connected, as with sealing, to open hole at the center of a baffle plate, and then the baffle plate was attached to the end of sound tube made by transparency acrylic pipe with internal diameter of 100mm. A pair of microphones with slightly separated positions was set in front of test sample and white noise sound source was radiated from the opposite end of the tube toward test sample. Received microphone output signals were led to a personal computer by using digital signal processing instruments and software.

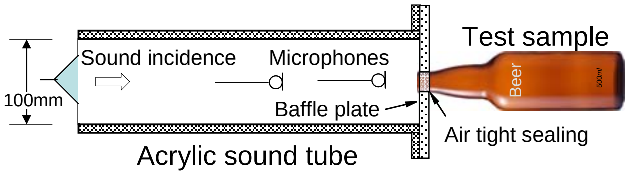

Figure 1. Outline of measurement of sound absorption characteristics of bottle by sound tube method.

And then, sound absorptive characteristics of the test sample were analyzed as following transfer function method of the ISO by using FFT software (10). Some additional analyses on the obtained sound absorption characteristics were done by use mathematical calculation software for deeper considerations on them.

SOME MEASURED RESULTS OF ACOUSTIC IMPEDANCE AND SOUND ABSORPTION COEFFICIENT

Examples of acoustic impedance and sound absorption coefficient obtained in trial experiment for a beer glass bottle with net capacity of 500 ml are shown in "Figure 2.(A) , (B)". In these figures, we can find out the zero crossing in imaginary part of acoustic impedance and high peak in basic sound absorption coefficient at frequency of about 150 Hz. So, we can confirm sound resonance phenomenon in the beer bottle. However, peak of sound absorption coefficient is not high as about to be 0.5.

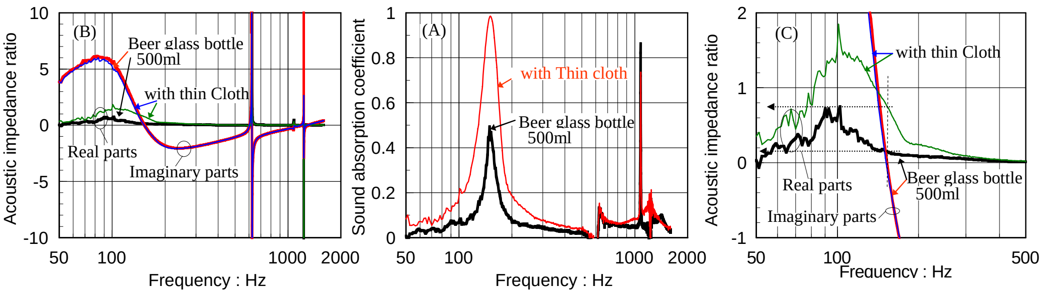

Figure.2 Measured sound absorption characteristics of a glass bottle for beer.

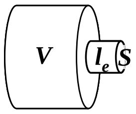

Figure 3. Ideal model of Helmholtz's resonator.

Test sample of glass bottle for beer introduced just above has partially tapered off shape toward narrow open mouth from swelled main body part for storing liquid beer, and it looks like a structure in kinds of Helmholtz resonator which has wide air space behind a little long and thin neck continued to narrow open mouth. Ideal model of Helmholtz resonator is shown in "Figure 3.", it is formed by open mouth and neck part with section area S and with the effective neck length l_e and by backing air space with volume V, and then theoretical resonance frequency is given by "Equation (1)."

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{Vl_e}} \qquad (1)$$

From some assumptions as both of S and l_e were simply given by measured diameter of open mouth of 18 mm and length of "neck-like" part of 65 mm even with tapered shape, and V was given to be 500 ml by nominal net capacity, then Helmholtz resonance frequency was calculated to be 139 Hz. The calculated frequency roughly corresponds, even slightly low, to analyzed resonance frequency of 150 Hz.

We concluded that Helmholtz resonance phenomena would cause in many kinds of glass and plastic bottle overflowed in our environment, and sound absorption coefficient of this sample kept low value not suitable for practical use.

Therefore, we tried additional experiments to increase sound absorption at resonance frequency by thin cloth covering open mouth as the same way as setting of fibrous material just behind of holes of perforated plate.

Measured and analyzed results are shown in the same figures to compare with the original characteristics in "Figure 2.(A), (B)", and partially zoomed acoustic impedances shown in "Figure 2.(C)". It can be confirmed that sound absorption coefficient increases as shown in "Figure 2.(A)" and it can be see that real part of acoustic impedance at resonance frequency closes to the value of 1 which means high sound absorption.

From a point of view of environment problem, recycling use of many empty bottles as they are or with a little treatment for some purposes is very effective instead of burning as just garbage. Authors looked forward that bottles for storing liquid or powder materials would cause sound resonance and effective sound absorbing in wider frequency range.

MEASUREMENTS OF SOUND ABSORPTION CHARACTERISTIC OF USED BOTTLES.

We made more experiments and considerations on them. We selected various bottles for test samples made by glass and plastics as PET to store drink water for large volume of 2000 ml and glass bottles of 633 ml for beer and small one of 50 ml for whisky and very small plastic bottle of 7 ml for storing

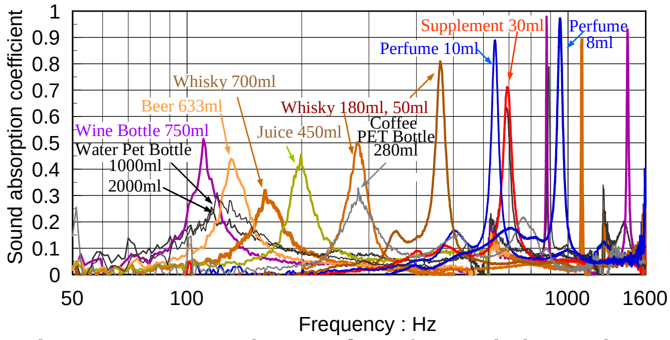

Figure 4. Measured examples of sound absorption coefficient of bottle with different net capacity.

cosmetic materials. Some light metallic bottles for beverage storing also selected for comparisons. Obtained frequency characteristics of sound absorption coefficient of typical samples are shown in "Figure 4.".

There are both clear dependences of resonance frequency and sound absorption coefficient on the net capacity of bottle. Larger capacity causes resonance at lower frequency and lower sound absorption, and smaller bottles have higher resonance frequencies and higher sound absorptions.

The range of the resonance frequency change is 10 times as from lower 100 Hz to higher 1 kHz for capacity change of 300 times as from the largest 2000 ml to the smallest 7 ml. Peak value of sound absorption coefficient changes from 0.3 at the low frequency to almost 1 at the high frequency of 1 kHz.

Dependences of resonance frequency and sound absorption coefficient on net capacity of bottle

"Figure 5." shows data plots of resonance frequency against net capacity of bottle, and character 'G' in this figure means datum for glass bottle and 'P' means datum for plastic bottle made by Poly Ethylene Terephthalate or Polyethylene. In this figure, it seems that relation between net capacity V and

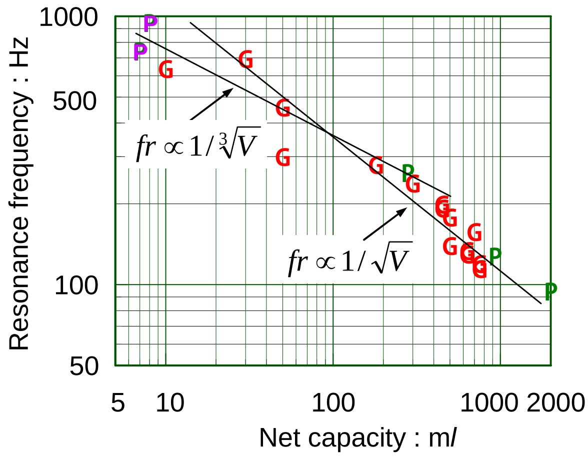

Figure 5. Relations between net capacity of bottle and analyzed resonance frequency.

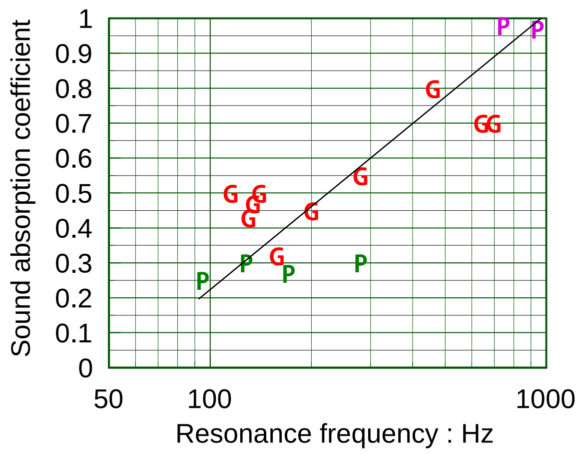

Figure 6. Relations between analyzed resonance frequency and sound absorption coefficient of each test sample bottle.

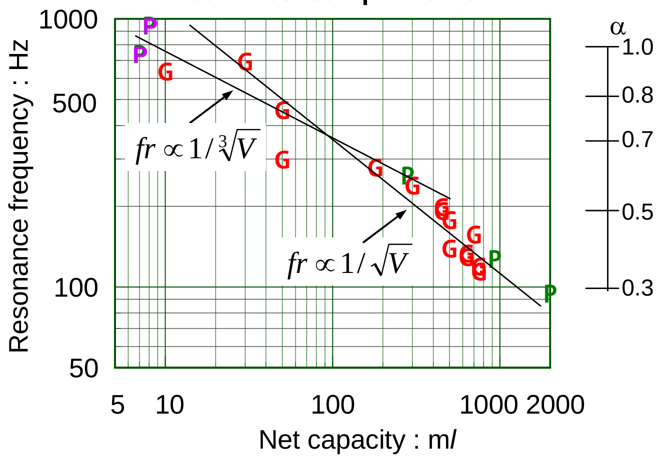

Figure 7. Relations among net capacity of bottle, analyzed resonance frequency and sound absorption coefficient on each test sample bottle.

resonance frequency f_r roughly mach to the approximation formula of " $f_r \propto V^{1/2}$." Consideration on the formula with referring the theoretical "Equation (1)," determining resonance frequency, leads the presumption that ratio values of S/le are almost constant for many test samples even with different sizes and shapes. Such presumption is roughly convinced from the fact that many examples of PET have the same shape in short neck and open mouth part with the common size of cap.

On the other hand, the relations in partial plots for small and medium bottles have a little good matching to another approximation formula of " $f_r \propto V^{1/3}$ " shown in the same figure. The later approximation means that size relations among open mouth, neck and main body part in small or middle bottles have proportionality in their shapes.

So, we can estimate the resonance frequency of typical empty bottles for storing beverage etc by according to these relations. Next, consideration was also done about one more important values of the sound absorption coefficient.

"Figure 6." shows plots of each relation of sound absorption coefficient in untreated states without any resistant material over open mouth against of resonance frequency. And, character signs of "G" and "P" in this figure have the same meanings as shown in the former "Figure 5.". There is tendency that the sound absorption coefficient increases as the resonance frequency rises.

The acoustic resistance of simple Helmholtz resonator is basically depend on both section area of open mouth and neck, effective length of neck part and on frequency. For example in the case of typical perforated plate, the dependence is well known(11).

In the case of bottles with various shape and different from ideal Helmholtz resonator, it had be difficult to determine exact sound absorption coefficient. But now, rough estimation of sound absorption coefficient in the typical bottles can be done by referring "Figure 6." after estimating sound resonance frequency by the relation shown in "Figure 5.". It can be thought that scale for converting to sound absorption coefficient based on the relation as in "Figure 6." should be put at the right side of "Figure 5.". So, authors newly made "Figure 7.".

Then, we need only net capacity of object bottle to estimate both representative values on sound absorption characteristics.

However, these results above mentioned were obtained by experiments for single object bottle in the condition using sound tube with diameter of just 100mm. For the different ideal case as plural smaller test samples and for the cases as wider or narrower evaluating area than original section area of sound tube, we need calculation to estimate the ideal sound absorption coefficient as follows.

For the increasing of number of test bottle from one to n, we can obtain acoustic resistant x from the sound absorption coefficient of single resonator, and based on assumption that acoustic resistance x at each open mouth of a bottle keeps the same value, we can re-calculate the ideal absorption coefficient α by following "Equation (2)."

$$\alpha = \frac{4x/n}{(1+x/n)^2} \tag{2}$$

Then, total acoustic resistance for plural resonators simply decreases than that of single resonator, value x lower than 1 brings more low sound absorption coefficient, and the value exceed 1 may bring higher sound absorption. And sound absorption coefficient can be also obtain in the case for the low density arrangement of resonators in wider area by giving virtual number of decimal n lower than 1.

NUMERICAL CALCULATION WAY OF SOUND ABSORPTION CHARACTERISTICS OF BOTTLE

There are many bottles with different shape, and we can not be sure they belong or not in kinds of Helmholtz resonator. And then, we face to difficulty of estimating sound absorption characteristic.

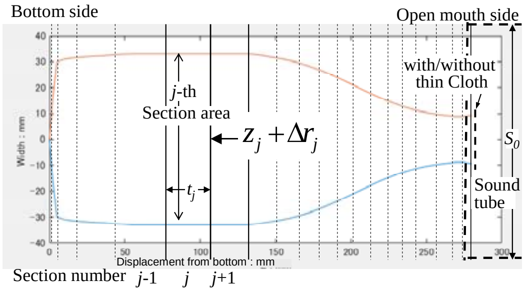

Figure 8. Air space layer model with different section area in each depth in bottle

Therefore, we considered the exact way to calculate sound absorption characteristics for variously shaped bottles. Calculation model with only two assumption having narrow opening and swelled main body is shown in "Figure 8.". And it has accumulation of air layer divided according to the area change in the cross section. Then, we can continuously calculate acoustic impedance z_j at surface of j-th layer from bottom to open mouth by using following recurrence "Equation (3)," based on the introduced equation by C. Zweker and C. W. Kosten (9, p2),

$$z_j = (z_c / s_j) \frac{z_{j-1} \coth(\gamma t_j) + (z_c / s_j) \sinh(\gamma t_j)}{z_{j-1} \sinh(\gamma t_j) + (z_c / s_j) \cosh(\gamma t_j)} + \Delta r_j \qquad (3)$$

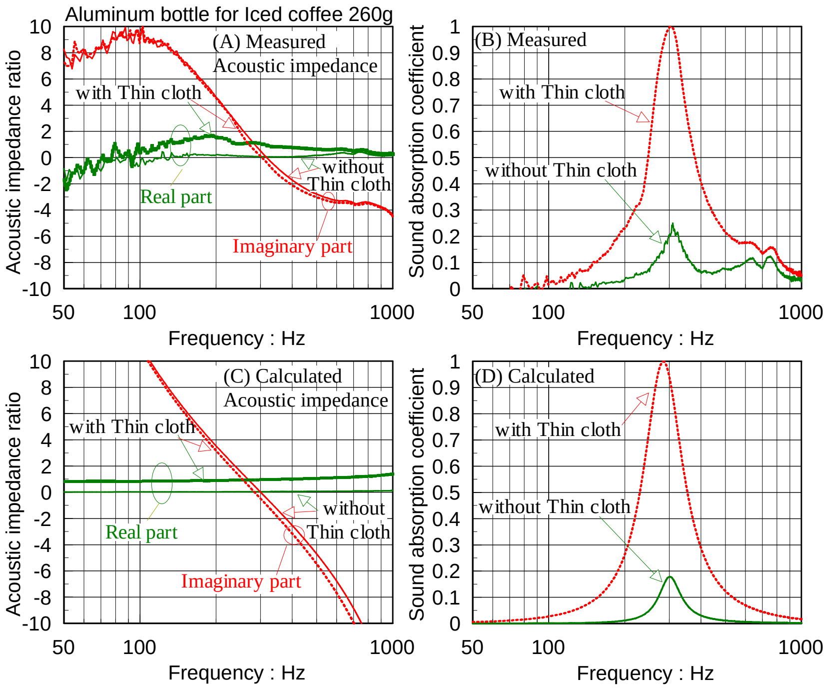

Figure 9. Comparisons of measured and calculated sound absorption characteristics of aluminum bottle with net capacity of 260ml for both conditions with and without a thin cloth over the open mouth.

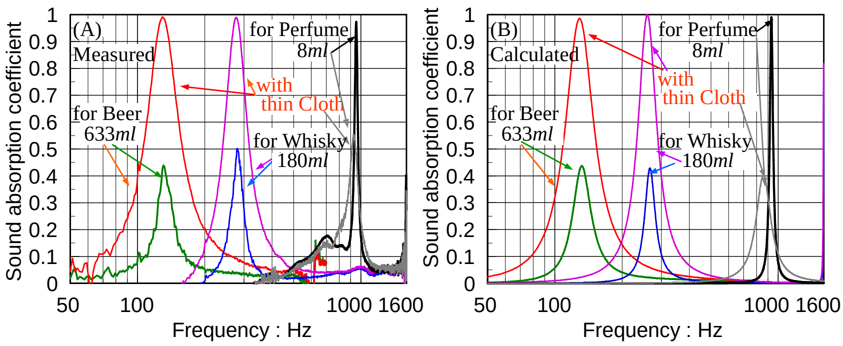

Figure 10. Comparisons of measured and calculated sound absorption coefficient for three kinds of bottle with different net capacity.

with giving each thickness, section area, complex sound propagation constant and characteristic acoustic impedance of filled medium. Both of sound propagation constant and characteristic acoustic impedance for each air layer correspond to wave number and acoustic impedance in the air. And the acoustic resistance for narrow section parts as neck or open mouth is added based on dependencies to frequency, from -2nd to -3rd power of diameter of cross section and length of the parts. Moreover, it could be understood that slightly lower resistant value was suitable to make good matching to the measured results of acoustic impedance at the opening of bottles than the resistant value for the case of perforated plate with narrow opening holes (4).

According to the consideration just above, we made some measurements and test calculations. Measured and calculated examples of acoustic. impedance and sound absorption coefficient of the aluminum bottle with net capacity of 260 ml are compared in "Figure 9." And it can be understood that the both frequencies appearing peaks of sound absorption coefficient are fairly matched.

The results with high sound absorption by a thin cloth covering open mouth of the same bottle are shown in the same figures. Acoustic resistance in the calculation was given based on the virtual substitution using material with already-known propagation constant instead of actually used thin cloth. We gave the propagation constant and characteristic acoustic impedance of glass wool with density of 32 kg/m^3, and gave virtual thickness as basically to have the same weight par unit area between glass wool and used thin cloth.

To make sure that this calculation way would be available for various kinds of bottle, we made some calculations with wider range of capacity from both glass bottles with net capacity of 633 ml and 180 ml to small plastic bottle with 7 ml for storing cosmetic liquid material. Obtained examples are compared in "Figure 10.", and it can be sure that these correspond well. It can also be judged that this calculation way to estimate sound absorption characteristic is effective even for various bottles or vessels with difficulty of clear dividing between both parts of neck and main body part.

MEASURING EXPERIMENTS FOR ACTUAL APPLICATION

When we apply the obtained results from measurement and calculation to the practical use as for acoustical control, there is a advantage in bottles as PET making individual sound resonance effects compared with perforated plate making only uniform effect even by wide constructed area. However we cannot use the obtained sound absorptive characteristics of various empty bottles as for acoustical control onto object space. For example in the setting, we have to understand the different between both characteristic with and without baffle plate around open mouth. Authors tried additional measurements by bottle set inside sound tube.

Measurements on bottle set inside sound tube

We exchanged the baffle plate for simple hard plate at the end of the sound tube and laid test sample just in front of the hard plate in the tube as shown in "Figure 11.".

Newly obtained both examples of acoustic impedance and sound absorption coefficient of PET with net capacity of 280 ml and with short neck part are shown in "Figure 12.", and measured results by ordinal setting are compared.

In the datum of the test sample set outside and connected through the baffle plate, the peak of sound absorption coefficient is appeared at resonance frequency of 280 Hz and other peaks with a little high value at frequencies of 700 Hz or higher frequencies are appeared.

On the other hand, in the new datum of the sample set inside and without baffle, the peak value at the same frequency of 280 Hz increases as to be 0.7, and peaks of 0.5-0.3 are appeared at the frequencies from 500 to 700 Hz.

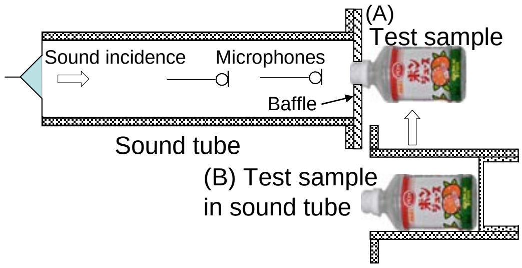

Figure11. Measurement method of sound absorptive characteristics of bottle inside of sound tube.

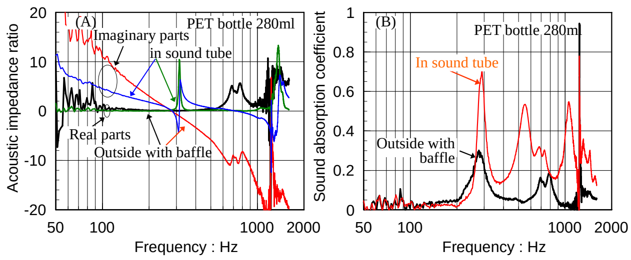

Figure 12. Measured examples of sound absorptive characteristics of a PET for storage of juice in the different setting condition.

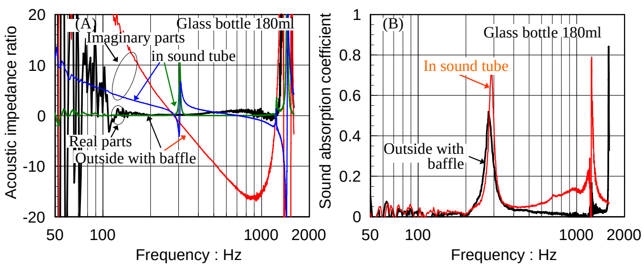

Figure 13. Measured example of sound absorptive characteristics of a glass bottle for each setting condition.

"Figure 13." shows the results obtained from the comparative measurements for hard glass bottle with net capacity of 180 ml and with a little long neck part. In the results for the test sample at outside of sound tube with connecting by baffle plate, the peak of the sound absorption coefficient of 0.5 is appeared at the coincident same frequency of 280 Hz. And, the sound absorption coefficient newly obtained for the test sample set in the sound tube increases as to becomes 0.7 at the resonance frequency.

We can understand that there are no high peaks within higher frequency area to be observed and evaluated with limiting by our measuring system using the sound tube. From these results and their comparison, we can understand that baffle plate makes sound wave flow through opening between inside and outside easy. Then, baffle-less makes sound absorption coefficient higher for the case that real part of original acoustic impedance is lower enough than 1.

Influence of acoustic-vibration excited on plastic bottle.

We made the same subsequent tests as for the aluminum metal bottle with net capacity of 260 ml for storing beverage, with hardness, and even with light weight as PET, then we could confirmed that only sound absorption of fundamental sound resonance was appeared in the test results. Based on these comparisons on the measured results introduced just above, we can guess that plastic bottle with light weight and flexibility make easy excitation of characteristic vibrations within frequency area to be observed and evaluated, and certain influences are brought as that imaginary sound absorption phenomena are appeared with strength especially on the test sample set inside the sound tube.

We can conclude that strength of acoustical excitation on the characteristic vibration on the surface of bottle determine which imaginary sound absorption is high or low. Excitation on the bottle set outside is weak, because sound wave pass through narrow opening of baffle plate. And excitation on the bottle set inside is strong, because sound wave directly reaches. Excitation of vibration needs sound energy and it will attenuates, at last, these acoustic-vibration phenomenon brings a kind of measurable sound absorption, and brings change of the acoustic impedance as increasing of resistance attenuating sound energy. The sound absorption characteristic is observed as the combined effects due to fundamental Helmholtz resonation and to excitation on characteristic vibration.

So, Authors though of method to catch the only effect due to characteristic vibration by capping mouth not to excite Helmholtz resonance in the test bottle. The examples of measured result of capped PET with capacity of 280 ml and 500 ml are shown in "Figure 14.". And examples of both capped bottle made by glass or aluminum metal are shown in the same figure. At first, it can be confirmed that the fundamental sound absorption characteristics originated in Helmholtz resonance is disappeared by capping on the open mouth of test samples set inside the sound tube. Next, it can be

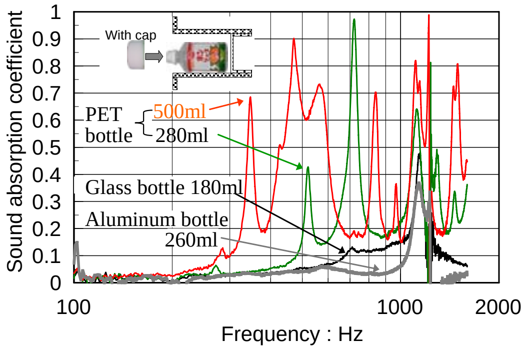

Figure 14. Comparison of sound absorption coefficient of various bottles with different forming material.

also confirmed that two or more over peaks of remarkably high sound absorption coefficient are appeared in higher frequency area in the same figure for the capped PETs.

On the other hand, we can see no-peak of sound absorption originated in fundamental Helmholtz resonance nor peaks originated in characteristic vibrations on capped test bottle made by glass or aluminum.

Measured results of light and soft plastic bottle have sound absorptive characteristics originated in Helmholtz resonance and that of influenced by characteristic vibration for each sample setting condition as inside or outside. Both phenomenon will be appeared separately or with overlapping according to their structural forming, size, weight and their material properties. We have to confirm their influences by experiments with changing set condition of test sample as mentioned above and/or by calculations of sound absorptive characteristics originated in Helmholtz resonance.

For the preliminary study, we introduce that excitation of characteristic vibration on plastic bottle can be easily, not exactly, catch by sound receiving on the bottle surface and its sound analysis when softly knocked.

CONSIDERATION OF SOUND ABSORPTION OF BOTTLES SET INTO GENERAL ENVIRONMENT.

If we will think of over flown empty bottles from the point of view of effectiveness of their acoustical function, at least we have to understand exact acoustic characteristics to mach the simplest actual setting of bottles in general environments. Influence by existence of baffle plate around open mouth on sound resonance and effect by excited characteristic vibration of the object bottles should be understood and be considered.

As for first easy way of both understandings, if object bottle is small enough to set inside sound tube, measurement of sound absorption characteristic without baffle directly give us both components. As for secondary way for large object bottles not to be laid inside sound tube, but we can estimate effect of baffle less condition by following procedure. At first, we have ound absorptive characteristics with baffle plate by reading-out from "Figure 7." or by our calculation way used "Equation (3) introduced before.

For easy understanding in this consideration, we use acoustic admittance determined by the relations among acoustic impedance, sound absorption coefficient. Admittance β_{h_out} is due to measured effect of the Helmholtz resonance in the object bottle with setting outside sound tube and with the baffle plate.

If it is assumed that baffle-less makes sound wave flow through open mouth weaken, admittance value decreases.

So, we evaluate weakened effect by multiplying of ideal correction constant c_{no_baf} (<1) on the admittance. In addition, we consider the effect of characteristic vibration by admittance value β_{vib} based on the same relations with acoustic impedance and sound absorption coefficient measured for the capped test bottle with setting inside of sound tube. Ideal admittance including both components β_{add} is convert to its inverse value of acoustic impedance z_{calc}. At last, sound absorption coefficient α_{calc} is calculated as corresponding to the effects of sound absorptive characteristics by individual target bottle making influence in the environment. If target bottle is made by glass or metal, β_{vib} is assumed to be zero.

We made some measurements to evaluate adaptability of the following "Equations (4), (5)" explained just above.

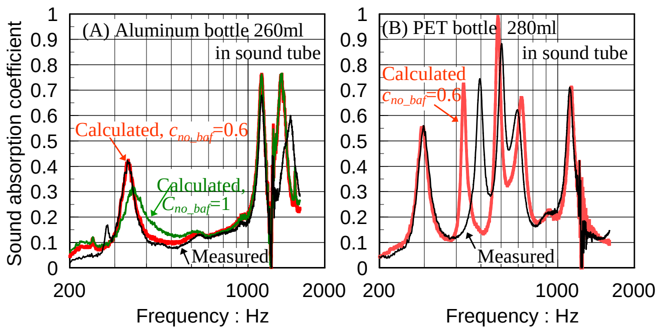

Figure 15. Comparisons between estimated sound absorption coefficient and measured ones for the test bottle set inside sound tube.

$$\beta_{add} = c_{no\_baf}\beta_{h\_out} + \beta_{vib} = 1/z_{calc} \quad (4)$$

$$\alpha_{calc} = 1 - \left|\frac{z_{calc}+1}{z_{calc}+1}\right|^2 \quad (5)$$

Good fit examples between measured result and calculated one based on "Equation (4), (5)" with giving ideal value lower than 1 to c_{no_baf} are shown in "Figure 15.". It can be confirmed that both match at resonance frequency by giving value near 0.5, and roughly match even in frequency area of characteristic vibration effects.

Test measurements for large capacity bottle thicker than standard sound tube should be tried by using of partially thick end parts to make inside setting able.

In this stage of our research work, difficulty remains to make exact measurement and fitting in the case that effect of characteristic vibration have overlapping in the frequency area of Helmholtz resonance. Both effects are combined not to be separately understood, but to be evaluated as they are mutually influenced.

EXAMPLES OF TREATMENT FORWARDING MORE PRACTICAL USE

At last, authors introduce examples of simple ideal treatment for improvement and increasing acoustical value on sound absorption characteristics of bottles.

Selection of bottles

Selection of bottle is very important to accomplish intents in its use. Our selection idea at first was based on general points of easiness for use, ecological economy and green building policy to mach the motivation of our research work. Our conclusions as follow. Plastic bottles have superiority than glass bottles. PETs are light weight, and they make condition free for setting part in building as available even on high ceiling. They are various in capacity, size and form. Suitable bottles can be got from many stocks of resources waiting recycling use. If we need new products of bottle, we can obtain

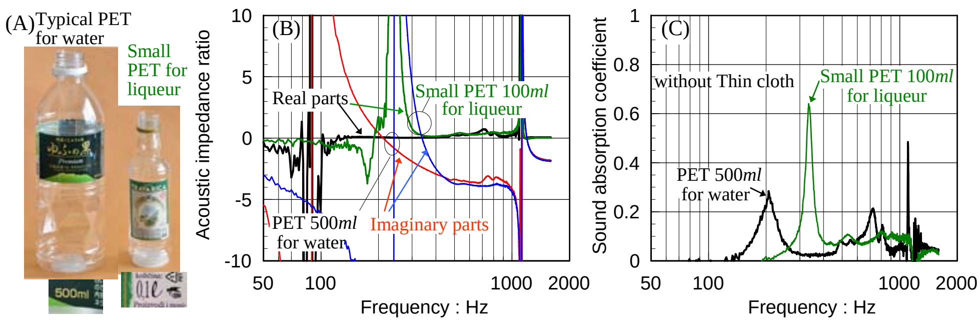

Figure 16. Selected typical and smaller bottles and their basic sound absorption characteristics to be improved for practical use.

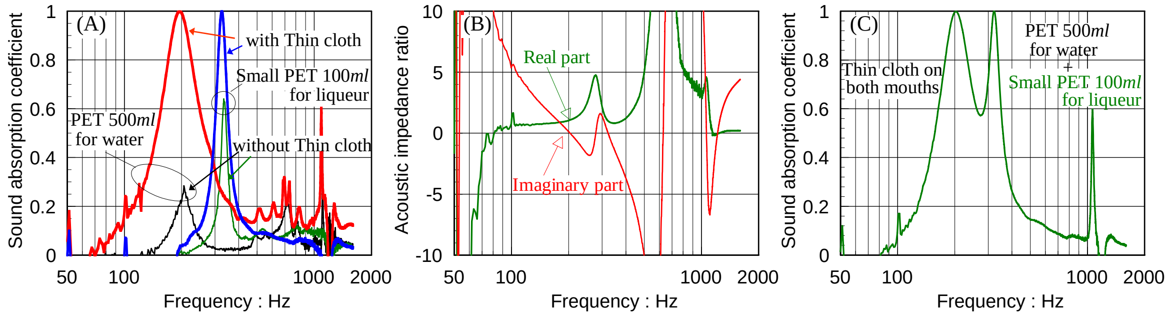

Figure 17. Improved examples to have high sound absorption by thin cloth covering open mouth and the characteristics of combined set of both bottles.

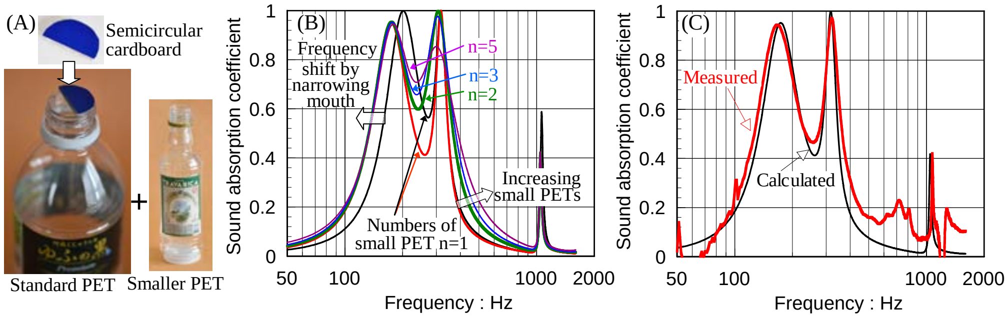

Figure 18. Simulated and confirmed high sound absorbing examples with expanded resonance frequency area to lower side by pseudo narrower opening and by multiple additional sets of bottle.

low-cost ones from mass production factory.

Of course, selection from a point of acoustical properties is important. Stiff bottle is good to avoid excitation of characteristic vibration on the surface of mail body part at the low and mid audible frequency. Spherical body and cylindrical shape are good. Light weight and soft flexible body and many-sided shape with plane parts are unsuitable, because they easily cause many characteristic vibrations which bring no-predictive pseudo sound absorptions combined with sound resonance in important audible frequency range.

Forwarding purpose of our trial

Our purpose was realizing high sound absorption for more wide frequency range. And we selected two PETs in this trial. One has most typical size and cylindrical body and spherical shape at connection between body part and mouth part. Its net capacity was most popular 500 ml, and height was 210 mm. Another was smaller one with capacity of 100 ml, and it could be judged that the smaller one would be suitable to be put in the narrow spaces among former ones in the combinational use.

Trial results

Selected PETs are shown in "Figure 16.(A)". And their basic sound absorption characteristics measured in this trail are shown in "Figure 16.(B),(C)". Each sound resonance is appeared at about 200 Hz and at about 300 Hz. As already introduced before, even for low sound absorption coefficient, it is easy to improve to obtain high sound absorption by several sheets of thin cloth covering open mouth as shown in "Figure 17.(A)".

As for selected both PETs in the combined state, we tried to measure sound abortion characteristics by setting of both PETs to the baffle plate with two holes by the same way as shown in "Figure 1.". Analyzed characteristics are shown in "Figure 17.(B),(C)". We can see the sound absorptive characteristics for wider frequency band than each sound absorption characteristics.

We tried to obtain sound absorption for wider frequency range, especially expanded to low frequency side. Treatment to lower resonance frequency on the typical PET was making open mouth narrower. We took very simple treatment putting semicircular cardboard on open mouth as shown in "Figure 18.(A)". And then, to accomplish our intents, we made some numerical simulation of sound absorption in combined state of two PETs by using calculation model as shown in "Figure 8." and "Equation (3)".

Simulations for the simple treatment could be easily made based on the models with changing form of open mouth. And authors estimated sound absorption characteristics for some ideal models, then we obtained sound absorption characteristics from calculations by "Equation (6)" and "Equation (5)".

$$\beta_{calc} = \beta_{res\_0} + \beta_{res\_1} + \cdots + \beta_{res\_n} = 1/z_{calc} \qquad (6)$$

Examples obtained from repeating of calculation are show in "Figure 18.(B)". Expanding of resonance frequency to lower side can be realized by semicircular cardboard putting on the mouth, high sound absorption and increasing of sound absorption coefficient value in mid frequency area between both resonance frequency also can be estimated. It looks like a valley of sound absorption filled by multiple PETs. To confirm exactness of simulated results, comparison between both simulated and measured results corresponding to the same condition is shown in "Figure 18.(C)". We can see that both are fairly matched, then we can conclude that this numerical simulation is available to find out good ways to use acoustical characteristics of PETs and improvements.

SUMMARY AND CONCLUSION

Sound absorption characteristics of the glass bottle and plastic bottles with various capacity were measured using sound tube method. Calculation way to understand sound absorption characteristics of bottles with various kinds of shape is proposed in this paper.

Then, authors can obtained following conclusions.

Resonance frequencies are in the range of 100 Hz -1 kHz when net capacity of bottles in the range of 2000-7 ml. Resonance frequency is lower as the capacity increases, and sound absorption coefficient is low as resonance frequency is low and it approaches to 1 as resonance frequency close to 1 kHz. These tendencies can be represented as simple relation and by approximate formulation.

High sound absorption characteristic can be brought on the original state with low characteristic by thin cloth covering open mouth.

The sound absorption characteristic can be estimated by recurrence formula to calculate acoustic impedance based on model of accumulating air layer divided by according to changes of section area from the bottom of object bottle to its opening. Calculation of the sound absorption characteristic for the covering open mouth by thin cloth is also available.

And, its good correspondence with the measured result could be confirmed.

The sound absorption coefficient is increased by set of test bottle into the sound tube from outside connection by baffle plate to the end of tube. It is the difference between of the condition with and without baffle around opening of Helmholtz resonator. Baffle plate makes acoustic impedance lower at the open mouth and changes sound absorption coefficient.

Plastic bottle with light weight and flexibility makes additional or imaginary sound absorptive characteristics according to their characteristic vibration excited on the framing surface.

Our research works can make clear that recycle use of glass and plastic bottles are very valuable for sound absorption. Low-cost sound absorption can be realize for wide frequency range by combination use, and high sound absorption can be easily tuned by adding very simple resistant material.

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