Computers and Electronics in Agriculture 147 (2018) 18–26

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Improved underwater Helmholtz resonator with an open cavity for sample volume estimation

Stephen N. Njane[a,*], Yoshiaki Shinohara[b], Naoshi Kondo[a], Yuichi Ogawa[a], Tetsuhito Suzuki[a], Takahisa Nishizu[c]

[a] *Laboratory of Bio-Sensing Engineering, Division of Environmental Science and Technology, Graduate School of Agriculture, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan*

[b] *Fisheries Technology Department, Kyoto Prefectural Agriculture, Forestry and Fisheries Technology Centre, Odashukuno, Miyazu City, 626-0052 Kyoto Prefecture, Japan*

[c] *Laboratory of Food Processing and Chemistry, Department of Applied Life Science, Faculty of Applied Biological Sciences, Gifu University, Yanagido 1-1, Gifu City 501-1193, Japan*

ARTICLE INFO

Keywords:
Helmholtz resonator
Volume
Closed
Open

ABSTRACT

Helmholtz resonators with an opening on the side of the cavity have the potential to improve the limitations of closed cavity resonators as a practical means for determining sample volume underwater. When inserting samples into a closed cavity resonator, a door must be opened, the samples inserted and the door once more closed before commencing measurement. By incorporating an additional opening in the cavity, it could act as east access inlet for samples, as well as an entrance for live aquatic samples in the future. However, the characteristics of such an open cavity resonator are unknown, as is the mechanism for generating resonance in such a resonator. This acts as a barrier to the design and optimize these resonators. To overcome these issues, we first characterized the relationship between flow velocity and the region where Helmholtz resonance is generated. From this, we determined the optimal flow velocity to generate Helmholtz resonance in the cavity, taking into account the energy required to generate the signal, as well as avoiding unstable resonance generation regions. Our results demonstrate that the flow characteristics of an open cavity resonator are more stable with less jumps in frequency, than a closed cavity resonator. Moreover, for design optimization, we determined the cavity to sample volume ratio that gives the most sensitive resonance results. To do this, we used empirical equations to analyze the ratio of cavity volume to sample volume and demonstrated that a high cavity to sample volume ratio is preferable for a less dense sample (compared to water), while a lower cavity to sample volume ratio is desirable for a denser sample. In addition, this was experimentally validated using model samples that were either less dense or denser than water. The linear regression model for denser samples accounted for R-squared (R^2) of 99.7% and 99.5% of the variance of the actual sample volume in the open and closed cavity resonators, respectively. However, for less dense samples, the model accounted for R-squared (R^2) of 97.5% and 99.3% in the open cavity and closed cavity resonators, respectively. These results demonstrate that precise and non-invasive sample volume estimation is possible with an open cavity resonator, which can also be used as inlet in the future for aquatic sample insertion and volume estimation.

1. Introduction

In aquaculture, volume measurement is important for determining the density of the products (Chen and Sun, 1991). However, aquatic products vary in their shape and size making volumetric parameters, which are useful for sorting, sizing and grading (Abbott, 1999; Gall, 1997), difficult to determine. To get around this limitation, measurements of volume have traditionally been done by using liquid displacement methods. However, such methods are time consuming and difficult to implement in large production facilities. While underwater camera systems can be used to sort size, species and length of fish and monitor fish feeding in pens (Spampinato et al., 2008), but they are also expensive, time consuming, and limited in their use, especially in murky waters. Thus, the development of a fast, reliable and non-invasive underwater volume estimation system is desirable.

We introduce a new rapid measurement technique known as Helmholtz resonance. This technique has been applied in air for successful measurement of watermelon density (Diezma-Iglesias et al.,

* Corresponding author.
E-mail address: njane.njehia.64r@st.kyoto-u.ac.jp (S.N. Njane).

https://doi.org/10.1016/j.compag.2018.02.015
Received 7 June 2017; Received in revised form 6 February 2018; Accepted 10 February 2018
Available online 22 February 2018

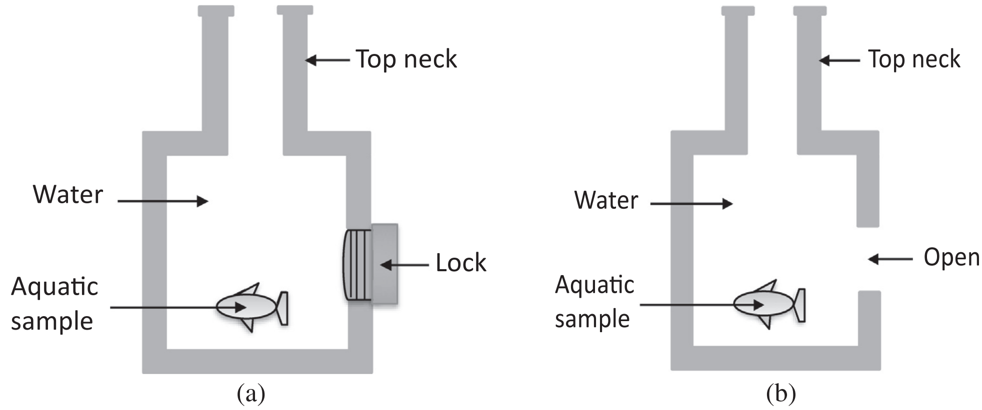

Fig. 1. Resonator cavities when (a) closed (b) open for aquatic samples' volume estimation. Top neck is for resonance generation.

2004), liquid volume (Nakano et al., 2005) and food products (Nishizu et al., 2001). However, due to the relative incompressibility of water (compared to air), the theory and the mechanism for resonance generation in water (exploiting differences in the bulk modulus between water and the sample) and its application to *in-situ* water measurements has been left unexplored.

Moreover, for a closed cavity resonator, the sole opening at the neck will be used for resonance generation (Webster and Davies, 2010), limiting the practical use of such a resonator. This is because a door or an additional lockable opening must be made for sample insertion and closed or locked once measurement is in progress (see Fig. 1(a)). This necessitates the need for an additional permanent opening into the cavity of the resonator that can act as an inlet for the samples and in the future underwater applications, be the entrance for live aquatic products, such as fish. A resonator that has another opening would have several advantages, including non-invasive measurement and the ability for future automation when measuring live aquatic products, as indicated in Fig. 1(b). However, development of an open cavity resonator has been impeded though by the lack of theoretical principles to aid in the optimal design and performance of such an underwater resonator. Thus, we set out to derive a theoretical model for open cavity Helmholtz resonators with an additional opening, and then to experimentally validate the derived empirical models and investigate the implications they have on the performance of this type of resonator.

In this study, we constructed a stainless-steel type resonating cavity with a neck for resonance generation and a permanent opening on the side of the cavity. The opening acts as an inlet for samples to be inserted (this opening is not closed during measurement) when measurement is underway. The neck, which generates resonance, has a whistle type nozzle and edge attached on top of it. To generate resonance, water is directed to the nozzle and edge at a specified flow velocity. However, in practice, it is difficult to determine the flow velocity at which resonating sounds will be generated due to overtones. We therefore designed an experiment where we compared both closed and open cavity resonators to determine resonance generation parameters when varying the flow velocity.

Yet another critical, but unknown, determinant of resonator performance will be the relationship between cavity to sample volume. This is important for future cavity design of the resonator in order to maximize the sensitivity for the expected sample volume given a particular cavity size (Kurdi et al., 2014). To do this, we first developed a theoretical model based on the dimensions of the resonators (both closed and open) to compare their performance. Deyu et al. (2007) has shown that optimally designing a resonator can improve its performance. The models were then used to simulate measurements of samples that are either denser, or less dense than water.

To validate the simulations derived from the empirical models, experimental prototypes of both (the closed and open) cavity resonators were constructed. For samples denser than water, glass balls were used, whereas for samples less dense than water, air was used for sample volume measurement.

2. Background and information

2.1. Derivation of Helmholtz resonance principles

The Helmholtz resonance mechanism can be explained by analogy to a mass on a spring. Taking the example of a PET bottle, when air is blown across the top of the neck, oscillation of air occurs at the top of the neck of the bottle. The air at the bottle's neck acts as a mass hence has inertia to oscillate and the air in the cavity acts as a spring to provide the stiffness in the cavity. This causes the pressure inside the cavity to increase. When the external force of air is removed, a pressure difference arises and thus, air tends to flow out of the cavity. However, due to the inertia at the neck, the air flowing out tends to overcompensate and hence causes the cavity to reduce pressure below that of the external pressure (Zhao et al., 2009; Soedel et al., 1973; Tang, 2005). Hence air is forced back inside the cavity of the resonator again.

The mass of air m (kg) at the neck of a closed cavity and the spring constant k (Pa) generates a resonant frequency f (Hz) given by Eq. (1) below:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

The same analogy and principle is used in water, where the mass of water oscillates at the top neck of the resonator. The cavity stiffness is provided by the water in the cavity of the resonator. By utilizing the bulk modulus property of water (K_w) and the dimensional properties of the resonator, an equation that represents the resonant frequency generated in the resonating cavity, can be derived as shown in Eq. (2) below:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_w}{\rho_w} \times \frac{1}{W} \times \frac{S}{l + l_{e1}}} \quad (2)$$

In water, the effect of the density of water (ρ_w) and the neck length (l) at the top of the cavity of the resonator, are important parameters in determining the resonant frequency. The additional length (l_{e1}) is the end effect correction of the length of the open end of the neck.

To a similar volume of cavity (W), an opening on the side of the cavity of the resonator is incorporated as shown in Fig. 2. This resonator has a top neck and a side opening. The top neck, has a cross-sectional area (S_1) and length ($l_1 + l_{e1}$). The top neck has the mass of water which oscillates and in turn generates the resonance. The opening on the side of the cavity has a cross-sectional area (S_2), and a neck ($l_2 + l_{e2}$). Samples are inserted through this opening for measurement.

For the open cavity resonator, a similar derivation analogy as that of