DETECTION OF AIR BUBBLES IN HP INK CARTRIDGES USING DYNAFLOW'S ACOUSTIC BUBBLE SPECTROMETER (ABS) TECHNOLOGY

Georges L. Chahine
Ramani Duraiswami
Gary Frederick

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DYNAFLOW, INC.
7210 PINDELL SCHOOL ROAD
FULTON, MD 20759

e-mail: glchaine@dynaflow-inc.com http://dynaflow-inc.com

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1. SUMMARY

This report describes the work performed under a feasibility study requested by Hewlett-Packard (HP) to determine if DYNAFLOW's Acoustic Bubble Spectrometer (ABS™) technique could be used to detect the presence of unwanted air bubbles inside HP's ink-jet cartridges and to assess the quantity of air. The Statement of Work specified:

"… DYNAFLOW, INC. will perform the following tasks:

1. *Examine HP's ink-jet cartridges and select a procedure to perform acoustical experiments on them.*
2. *Select a technique for introducing bubbles within the cartridges.*
3. *Measure acoustic signals in the presence and absence of bubbles, and determine the feasibility of detecting the bubbles in the liquid.*

Deliverables to HP under the contract will consist of:

- *A non-proprietary test report containing the results of the evaluation of the DYNAFLOW method of measuring bubbles in the ink-jet cartridges, and recommendations for future steps."*

The above tasks were performed successfully and acoustic tests cartridges provided by HP were conducted with and without air in the ink bags. These tests showed significant differences between the signals when bubbles were present or not. These differences increased with the amount of air present.

A summary figure from the tests is shown below, and demonstrates the detectability of air inside the cartridges using the ABS™ technology. *The method is seen to be able to determine the distribution of busses inside the cartridges even for very small amounts of air. This method has therefore potential to be adapted into a quality control instrument for HP.* However, in order to achieve these results the air gaps between the HP cartridge plastic bag and the mylar bag had to be removed to reduce strong acoustic interference. Consultations with HP engineers on how to address this aspect is required if the proposed ABS™ method is selected.

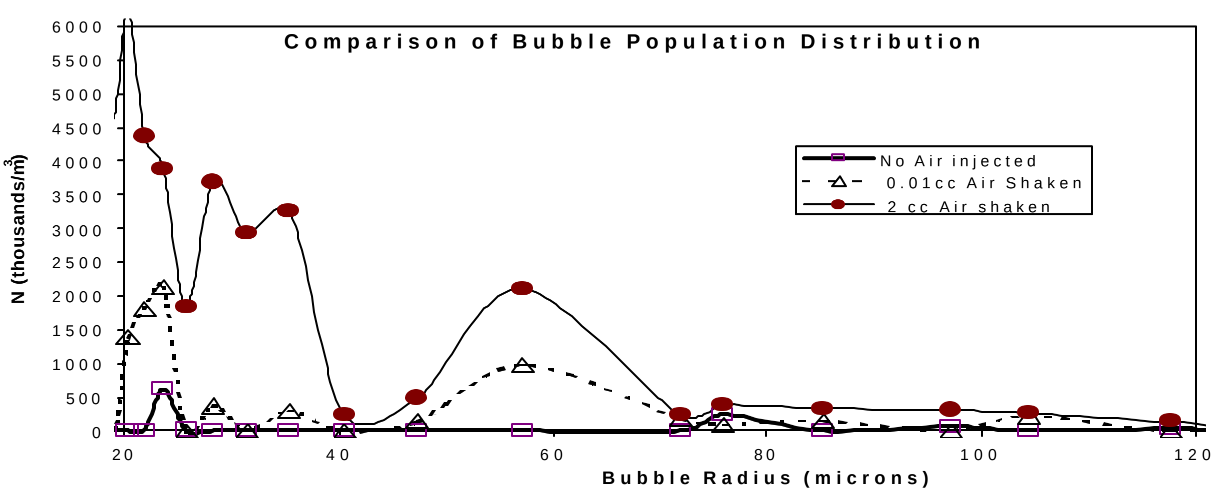

Figure 1: Bubble Size Distribution Determined by the ABS™ on HP Ink Cartridges with Mylar Bag Removed. Comparison of Original Cartridge (Squares), Cartridge Shaken With 2 cc of Air Injected (Circles), and Cartridge Shaken With 0.01 cc of Air Injected (Triangles).

2. BACKGROUND

Over the past several years DYNAFLOW, INC. has been developing the Acoustic Bubble Spectrometer, ABS™, an acoustic based method and instrument to measure bubble size distributions in a liquid [1-5]. Key features of the ABS™ are its ability to detect both bubble sizes and numbers and its potential for achieving near real-time measurements. The technology was initially developed in a two-phase program funded by the National Science Foundation (NSF) under the competitive Small Business Innovation Research program (SBIR). This technology is based on a long history of our involvement in bubble dynamics studies [6-12].

The ABS™ device is based on the principle that a bubbly medium is dispersive to acoustic waves. This means that in a bubbly liquid, as opposed to in a pure liquid, the sound speed and the attenuation characteristics of an acoustic wave depend on its frequency. The amount of dispersion is dependent upon the bubble population, which may be characterized by the bubble population density function, *n(a)*, defined as

$$\int_{a_1}^{a_2} n(a)da = \textit{number of bubbles between radii } a_1 \textit{ and } a_2 \textit{ in a unit volume of the mixture.} \quad (1)$$

Acoustic wave propagation in a dispersive medium can be conveniently described mathematically by considering the acoustic wave parameters including the speed of sound in the medium to be complex. Knowing the speed of sound in the pure liquid, c_l, the following *dispersion relation* provides the complex speed of sound in the mixture, c_m, for a wave of frequency f and angular frequency $\omega=2\pi f$:

$$\frac{c_l^2}{c_m^2} = 1 + 4\pi c_l^2 \int \frac{a n(a)}{\omega_0^2 - \omega^2 + 2i b\omega} da. \quad (2)$$

$c_m(\omega)$ is frequency dependent ω_0 and b are respectively the resonant frequency and the damping coefficient of a bubble of radius a insonified in the pure liquid at an angular frequency ω. This expression and the expressions for the quantities ω_0 and b are standard in the bubble dynamics literature and have been described in more detail for example in our Reference [1].

The ABS™ procedure uses Equation (2) to deduce the bubble population from measurements of sound attenuation and change in phase velocity at various insonification frequencies. Inverting the dispersion relation (2) results in two integral equations which relate the bubble density function, *n(a)*, to the sound speed ratio, u, and the attenuation coefficient, v, defined as follows:

$$u(f)=\frac{c_l}{c_m}, \qquad v(f)=\frac{c_l}{4\pi fd}\log\left(\frac{\overline{p}}{\overline{p}_{ref}}\right)^2 . \tag{3}$$

$\overline{p}_{\mathrm{ref}}^{2}$ denotes the mean square amplitude of the pressure signal measured at a distance d from the source when it is in the liquid in absence of bubbles, and $\overline{p}^{2}$ is the corresponding quantity in the bubbly liquid. Some details of the derivations and the numerical solution of the equations can be found in our previous reports [1-5].

The function of the current ABS™ instrument is to measure the quantities u and v defined above for various insonification frequencies. The inverse problem solution software that we have developed then deduces the bubble density distribution *n(a)*.

The following quantity, *N(a)*, provides the results in terms of the number of bubbles of a given size:

$$N(a)=\int_{a-da}^{a+da} n(a_*)da_*, \tag{4}$$

where $2da$ represents the 'bin' size. In the data reported below the bin size is 10 microns.

In order to use the method for a given liquid properties of the liquid needed to compute the above expressions are required. The expressions for the quantities ω_0 and b as functions of bubble size and insonification frequency should also be obtained. For the present study the liquid used is water for which all necessary quantities are known. In order to apply the technique to another liquid, such as ink, HP should either supply necessary data for the liquid, or an experimental determination of the necessary properties must be conducted.

3. EXPERIMENTAL PROCEDURES

3.1 Experimental Set-Up

After trying several preliminary set-ups that were not satisfactory, the following set-up was selected and used to conduct this feasibility study. No efforts were however spent on optimizing this configuration and its dimensions. An open Plexiglas chamber filled with water of internal dimensions 10×11×10 cm was used. Two opposing walls of the chamber were instrumented with flat acoustic transducers of dimensions 5×5 cm embedded in a soft voided polyurethane matrix 2 cm thick of dimensions 10×10 cm. The transducers have a resonance frequency of 150 kHz. One served as an emitter and the second as a receiver. A series of monochromatic signals were fed to the emitter transducer by a function generator. The emitted and transmitted signals were then recorded on a PC using data acquisition boards. The procedure was repeated over a selected range of frequencies, and the recorded signals were analyzed using the ABS™ signal processing software to obtain u and v as functions of frequency. These were then used to solve for $n(a)$ and $N(a)$.

The figure below shows a schematic of the experimental set-up used for the tests reported below.

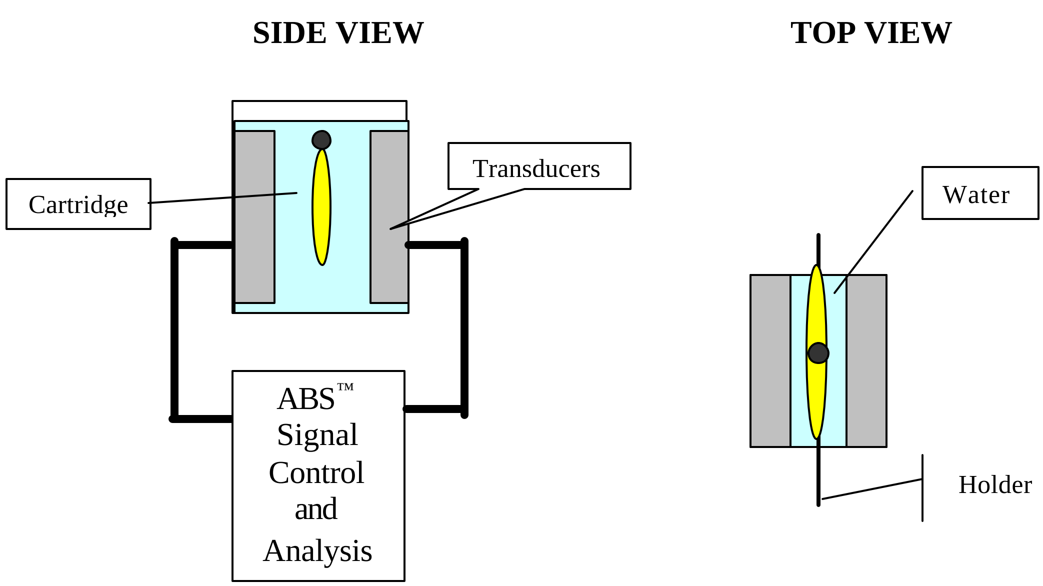

Figure 2: Sketch of the Set-up Used for Bubble Detection Using the ABS™ on HP Ink Cartridges

3.2 Ink Cartridges

The printer cartridges provided by HP have the following features. These cartridges consist of a pump assembly attached to a PVC frame, that supports a bag of ink simulant (water like). This frame is enclosed in a plastic case. The bag is made of two layers of materials. The first inner layer is made of a transparent plastic. This layer is protected on the outside by a second layer of aluminized mylar. It fast become apparent to us that the presence of air gaps between these two layers introduces significant noise in the acoustic response of the bag assembly. Initial trials of squeezing part of the bag between two transducers were not conclusive, especially since any unwanted air in the bag collects in the upper part of the bag where the frame is located. Later on, we found out that shaking the bag prior to testing significantly improves the detection process. This shaking procedure may be combined with the use of local transducers squeezing on parts of the bag, but we could not go back and test this idea within the constraints of the present study.

For all tests described below, the bag assembly was removed from the plastic enclosure and immersed in the middle plane parallel to the two transducers. When the tests are performed in this fashion with the mylar layer intact (as provided by HP) the bag assembly absorbs most of the acoustic energy emitted, and there is practically no received signal at the second transducer. It was hypothesized that the air gap between the plastic and the mylar was the cause for this loss. To confirm this hypothesis two bags with no air in them were selected and prepared as follows. In the first the mylar layer was removed, while in the second a small slit was cut in the mylar layer allowing the space between the plastic and the mylar to become filled with water. In both cases the bag assembly then became practically transparent to acoustic waves and no measurable damping of the acoustic signal was observed when compared with the base case: emission and reception in the same container in absence of a bag. We thus used, from there on, bags prepared in such a fashion to conduct the ABS™ air detection tests.

4. ACOUSTIC BUBBLE SPECTROMETER TESTS AND RESULTS

In order to assess the feasibility of the ABS™ technique, the following six sets of conditions were selected for testing, comparison, and reporting:

1. Water only between the two transducers.
2. HP bag with no air in it after removing gaps between mylar and plastic layers.
3. Bag similar to that in (2) but with 2cc of air injected into it.
4. Bag in (3) after shaking.
5. Bag similar to that in (2) but with 0.01cc of air injected.
6. Bag in (5) after shaking.

In order to inject a controlled amount of air in the HP bag a sharp hypodermic syringe was used and the air was squirted in via the cartridge injection port. The air injections were performed using accurately graduated scientific syringes.

The bubble distribution resulting from the air injection consisted of a few relatively large bubbles. To test the procedure for a distribution of smaller bubble sizes, the bags were shaken vigorously by hand, thereby causing a breakup of these large bubbles into many fine bubbles. Such a procedure strongly enhances the acoustic absorption if air is present, and is therefore very useful if the *objective of the test is to detect if air is present*, as opposed to determining the sizes of the bubbles in the bag at the time of the test. It should be noted that any distribution of small bubbles would slowly rise to the top of the bag and burst at the surface, leading to accumulation of an air pocket at the surface. Therefore, the ABS™ tests should be performed immediately after shaking is applied.

Figure 3 shows comparisons between several of the tests listed above. The results are shown in terms of the three characteristic quantities: the sound speed ratio, u, shown in Figure 3a, the attenuation coefficient, v, shown in Figure 3b, and the distribution of number of bubbles in a 10 micron bins per unit volume, $N(a)$, Figure 3c. These quantities were obtained by comparing the acoustic signals obtained with the bag placed at the center of the chamber with signals recorded in the absence of a bag.

Figure 3a shows that the sound speed is little affected by the presence of the bag when no air is present in between the two layers composing the bag. More significant, the presence of air in the bag when it is under the form of a few (or single) large cavities affects very little the measured sound speed. This is to be expected since the cross section of the air in the bag is very small compared to the size of the transducers. Unless a two-phase medium is present between the two transducers, the acoustic waves travels unaffected in the liquid. When the bag is shaken, mixing of the air with the liquid creates such a two-phase medium, and sound speed is reduced (Note that $u>1$ corresponds to sound speed in the medium lower that in the pure liquid.) For the case shown in Figure 3 the sound speed appears to be reduced in the full range of useful frequencies.

Figure 3b shows the variations of the attenuation coefficient with the frequency. Here, we can see a small effect of the presence of the bag in absence of air. Both when the mylar is present but air is removed from the gaps between the two layers, and when the mylar layer is removed, relatively small attenuation of the sound waves at frequencies below about 60 kHz are seen. This attenuation is significantly increased when air is introduced in the bag. Before shaking the bag the attenuation is mostly at frequencies below 30 kHz (which corresponds to bubbles larger than 100 μm). After bubble shaking, smaller bubbles are generated and Figure 3b shows that the attenuation becomes noticeable for all frequencies covered by the transducers.

Figure 3c shows the result of the analysis using the ABS™ code in terms of number of bubbles of a given size in one cubic meter of water. The code detects a very small number of microscopic bubbles in absence of air injection. (Notice that with the amount of liquid in the bag, one bubble gives an N of the order of 100 on the graph.) A significant amount of bubbles is seen to be generated when the bag is shaken, and is very easily discernable from the background noise in absence of air injection. These three figures indicate that the introduction of the air causes clearly discernible effects in the measurements, and that these measurements can be used to determine air presence in the ink cartridges. However, in this figure a relatively large amount of air was used, and the same had to be demonstrated for a much lesser amount. This is done in the following figures.

Figures 4 and 5 compare the results when 2cc of air and when 0.01cc of air are injected in the bag. Figure 4b shows the attenuation coefficient curves in the two cases when the bag is not shaken, while Figure 5b shows this attenuation when the bag is shaken. In both cases, attenuation at the lower frequencies is much larger than the bag with no air injected, but this result is greatly enhanced when the bag is shaken. This is further confirmed in the curves N(a) presented in Figures 4c and 5c.

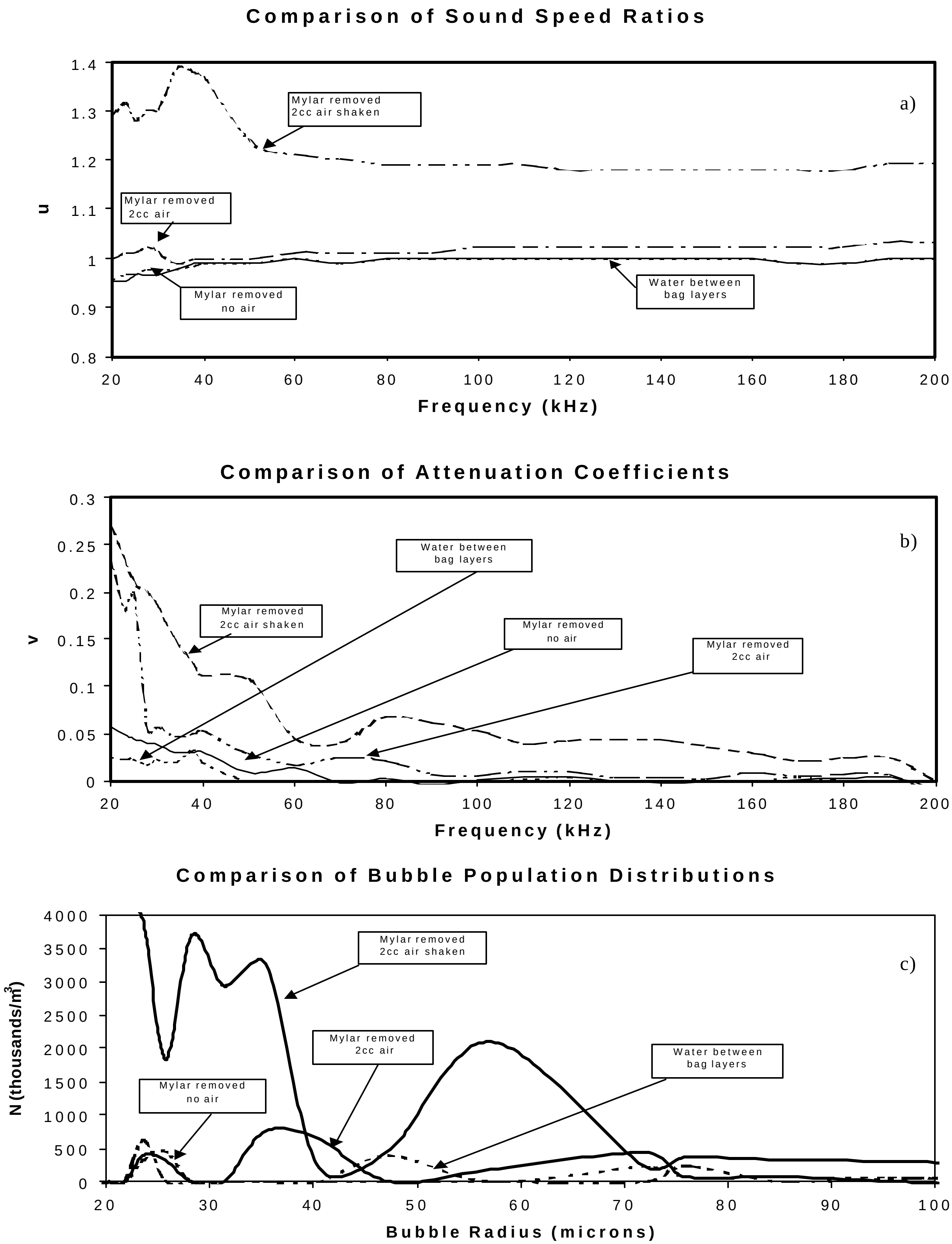

Figure 3. ABS™ Results for Air Detection in HP Ink Cartridges. Comparison Between Cases Where no Air was Injected and When 2 cc of Air Were Injected. a) Influence on Sound Speed Ratio. b) Influence on Attenuation Coefficient. c) Influence on Bubble Size Distribution.

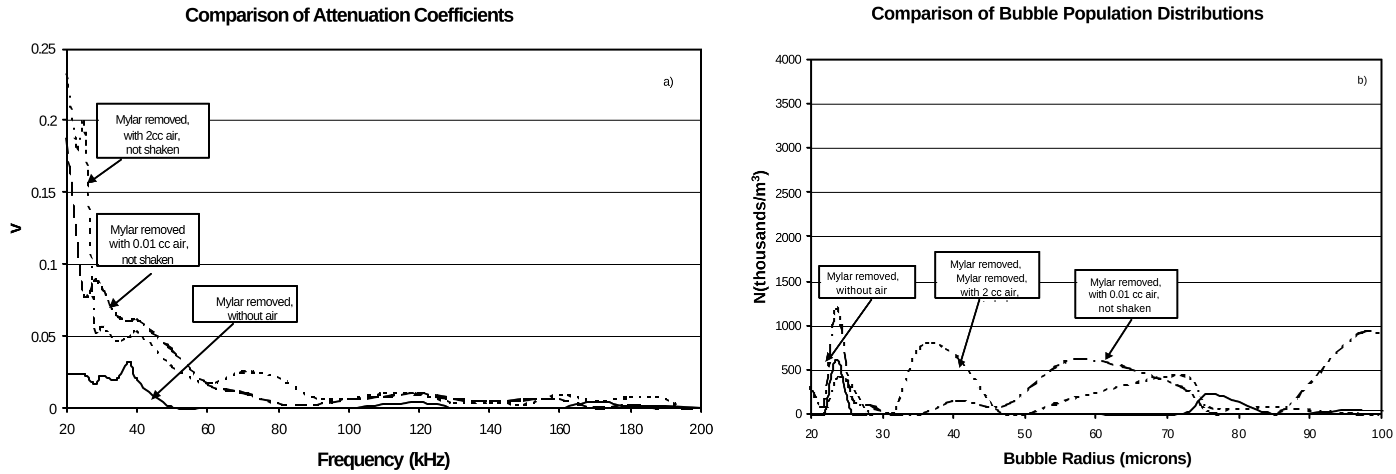

Figure 4. Comparison of ABS™ Test Results for Injection of 2cc and 0.01 cc of Air in the HP Ink Bags. The Left Figure Shows the Measured Value of the Attenuation Ccoefficient, While the Right Figure Shows the Resulting Bubble Population Distribution When the Bags Were not Sshaken.

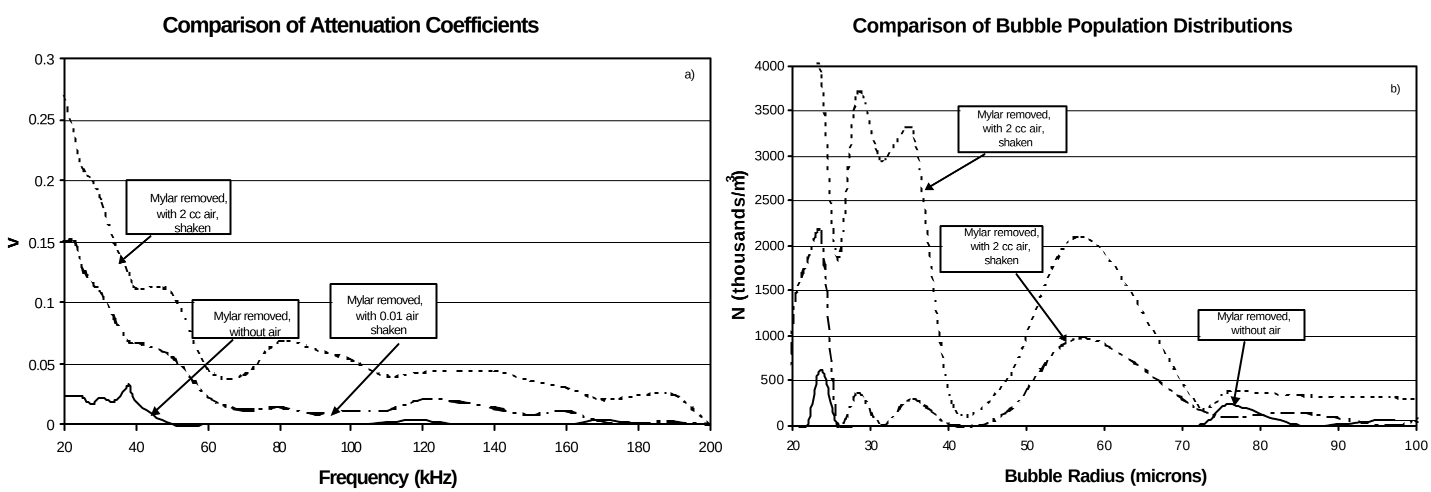

Figure 5. Comparison of ABS™ Test Results for Injection of 2cc and 0.01 cc of Air in the HP Ink Bags. The Left Figure Shows the Measured Value of the Attenuation Coefficient, While the Right Figure Shows the Resulting Bubble Population Distribution When the Bags Were Shaken.

5. CONCLUSIONS AND RECOMMENDATIONS

As a result of this preliminary feasibility study we can make the following conclusions:

1. The presence of air in the HP ink bags affects propagation of sound through the bag filled with a simulant, when this bag is immersed in water in between an emitting and a receiving transducer.
2. If the bag is shaken prior to the test, the injected air in the bag is transformed into microscopic bubbles that are very easily detected by the ABS™ technology.
3. These bubbles change the speed of sound and absorb acoustic energy from the sound wave.
4. Injected air of amounts as small as 0.01 cc is easily detected by the ABS™.
5. The presence of air gaps between the mylar and the plastic layer composing the bag affects very significantly the acoustic wave propagation.
6. Detection of the bubbles in the bag requires removal of these air gaps through air suction, water injection, or removal of the mylar layer. In a final instrument this problem needs to be addressed in order to automate the procedure.
7. Combining bag shaking and squeezing of the bag as is (no mylar removed) between tub small transducers may be an alternative solution that was not tested during this phase.

Based on the present study, we believe that the ABS™ technology provides the basis for a device and a procedure to perform quality analysis and sampling of bags produced by Hewlett-Packard in its assembly line.

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