Experimental study of sound attenuation by layers of water droplets

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Summary
Water-droplet suspension has been used as primary noise attenuation mechanism in the context of launching of space vehicles, where other attenuation mechanisms are hardly applicable. In this work, we present an experimental study of the attenuation properties of the sound transmitted through a multilayer structure of a saturated gas-vapor-droplet suspension. For this purpose, an experimental setup including a water injection system has been designed. To characterize the acoustic attenuation properties of the system, the dependence of the transmitted spectrum with the most significant parameters such as the droplet size, the spacing between nozzles and the pressure and flow of water in the system was measured.

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1. Introduction

The study of sound attenuation mechanisms is necessary to reduce damage in structures due to the coupling between the acoustic and the vibrational problem. This is the case of spacecraft and launch pads. The Sound Pressure Level (SPL) at the spacecraft in launch operations is of order of 200 dB. So high-pressure levels are problematic for both, the security of launch operation and the integrity of the load (as solar panels or antennas in satellites).
Sound suppression water systems are used at launch pad to reduce the noise impact [1-4]. A tower near the base of the pad holds the enormous amount of water that is released just prior to the engines ignition and flows using nozzles. The main goal is to reduce acoustical levels within the orbiter payload bay, by damping the energy reflected from the platform during liftoff and keeping noise levels below the design requirement.
In this work, a prototype of a simplified water injection system is designed, conceived and tested. This system uses water nozzles that inject a saturated gas-vapor-droplets suspension in order to attenuate sound. The main goal is to study the sound attenuation produced by suspensions in an incoming plane wave emitted by a broadband acoustic source. The influence on sound attenuation of several characteristics of the water injection system as droplet size, pressure and flow of water in the system and spacing between nozzles is considered.

2. Water injection system

The water injection system has been designed in order to generate a multilayer structure composed by three thin parallel planes of saturated a gas-vapor-droplet suspension (see Figure 1).

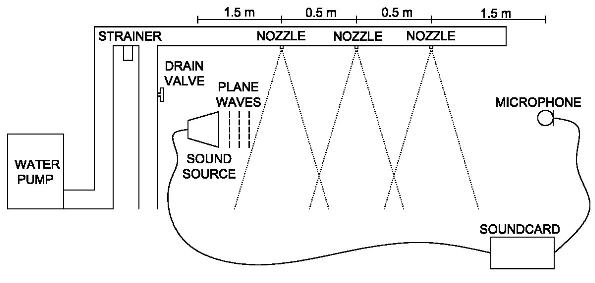

Figure 1. Scheme of the experimental setup.

A water pump injects a constant flow and pressure of water through a pipe. The pipe expels the water throw three nozzles separated at a fix distance, d=10cm. In order to prevent solid bodies that may obstruct the nozzles, a strainer is situated between the water pump and the nozzles. The water pressure is measured with a pressure gauge and controlled by a drain valve. The pressure water ranges from 1.5 bar to 4.0 bar with an accuracy of 0.5 bar. Three different interchangeable nozzles have been used. The droplet size and the water flow depend on the type of nozzles (see Figure 2).

1. Simple nozzles: TP series, (radii from 136 up to 218 μm),
2. Double nozzles, TTJ60 series (radii from 177 up to 428 μm) and
3. Water-induced nozzles, AI series, (radii from 218 up to 622 μm).

Figure 2. Types of nozzles: a) Simple nozzle, b) Double nozzle and c) air air induced nozzle

The water flow depends on the water pressure and the type of nozzle. In the designed system, it ranges from 0.65 L/min to 2.58 L/min.

3. Acoustic measurements

The acoustic system is composed by the sound source, a Cotpel enclosure, a Bruel&Kjaer 1/2' precision microphone, both controlled by a CLIO-FW soundcard. The signal used in all the experiments is an exponential chirp of size 65k. In order to reduce the noise 10 samples are averaged of 1.36s. Linear propagation of sound through the water droplets suspension is assured, as the signal intensity is lower than 1.6V.
The methodology to measure the sound attenuation α of the water injection system consists of measuring the Insertion Loss. Assuming that the viscous and thermic losses in the air are negligible, the Insertion Loss can be estimated as

$$IL = 10\log\left(\frac{\propto I_a}{I_a}\right) = 10\log(\propto) \qquad (1)$$

where I_a is the acoustic intensity of the source assuming that propagates plane waves.

As the experimental setup is outdoors, during sound acquisition the environmental noise is registered by the microphone. As well, the noise produced by the water injected by the nozzles must be considered. Thus, it is necessary to remove this external sources by evaluating them separately. To do so, four different measurements have been considered: 1) LP_{env} is the Sound Pressure Level of the environmental noise, 2) LP_{noz} accounts for the noise induced by nozzles and the environmental noise, 3) LP_a is the sound of the source (and the environmental noise) and 4) LP_{tot} accounts for all of the sources and the attenuation level.
Assuming that all sources are incoherent and that in air the Sound Pressure Level is approximately equal to the Sound Intensity Level:

$$LI_{env} = 10\log\left(\frac{I_{env}}{I_{ref}}\right) \qquad (2)$$

$$LI_{noz} = 10\log\left(\frac{I_{noz}+I_{env}}{I_{ref}}\right) \qquad (3)$$

$$LI_a = 10\log\left(\frac{I_a+I_{env}}{I_{ref}}\right) \qquad (4)$$

$$LI_{tot} = 10\log\left(\frac{\propto I_a+I_{noz}+I_{env}}{I_{ref}}\right) \qquad (5)$$

where IL is the Insertion Loss in dB, α□□□□□□□ attenuation coefficient, I_{env}, I_{noz}, and I_a are the acoustic intensities of all of the sources, environmental, nozzles and acoustic source, respectively.
Equations (2) to (5) define a system of 4 equations with 4 unknowns: α, I_{env}, I_{noz}, I_a, that can be solved to obtain the Insertion Loss of the water injection by replacing in equation (1):

$$IL = \log\left(\frac{10^{LI_{tot}/10} - 10^{LI_{tot}/10}}{10^{LI_a/10} - 10^{LI_{env}/10}}\right) \qquad (6)$$

4. Results and discussion

In order to study the influence of the selected parameters in sound attenuation, measurements and results have been grouped in three categories:

1. Measurements using simple nozzles only.
2. Comparative measurements of sound attenuation using simple, double or water-induced nozzles.
3. Measurements using different simple and water-induced nozzles combinations.

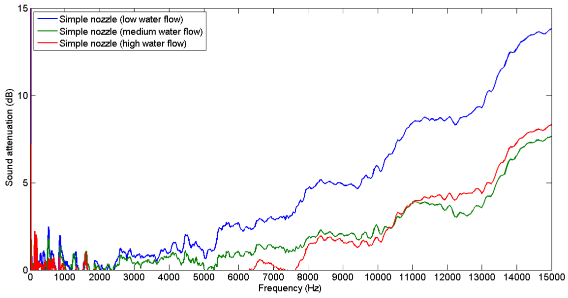

Figure 2. Sound attenuation using simple nozzles.

a. Measurements using simple nozzles

In order to characterize the influence of water pressure, in this part we have performed measurements by using three simple nozzles. The water pressure ranges from 1.5 bar up to 4 bar.
As seen in Figure 3, this type of nozzles produces a saturated gas-vapor-droplet suspension that presents an elevated sound attenuation at mid frequencies (1700 Hz to 1800 Hz, approximately), decreasing with the frequency increase.
The increasing of sound attenuation at these frequencies may be due to the water column thickness (10 centimeters) at the receiver device height (1.50 meters). Sound attenuation increases with water pressure, i.e, poner un ejemplo frecuencia SPL. This parameter has to be taken into account when designing a water injection system for sound attenuation.

b. Comparative measurements of sound attenuation using simple, double and water-induced nozzles

We study here the influence of different nozzle types in sound attenuation. For this purpose, we have used simple (TP11004), double (TTJ60-11004) and water-induced nozzles (AI11004). We have kept the water pressure fixed to a representative value (3 bar) in view of the results of previous section.
In Figure 4 we present the sound attenuation level in dB corresponding to configurations using one type of nozzle each one. The Sound attenuation at

mid frequencies using simple and water-induced nozzles is very similar. In contrast, at high frequencies (above 6300 Hz) the described trend changes: an increasing difference in favor of water-induced diffusers is observed. In the range between 1000 Hz and 500Hz simple nozzles seem to produce the best attenuation level.

Measurements and analysis of data suggest the hypothesis that the higher values of sound attenuation presented at high frequencies by water-induced nozzles could be due to the larger dispersion in droplet size with respect to the other types of nozzles. This would explain that, while in the case of the others nozzles the attenuation decreases, in this case remains high for a broad band.

In addition, mass flow may have suffered some modifications when nozzles have been changed, which could have change the medium impedance and its transmission properties.

c. Measurements using different simple and water-induced nozzles combinations

Up to here, the influence of the same types of the three nozzles has been studied.

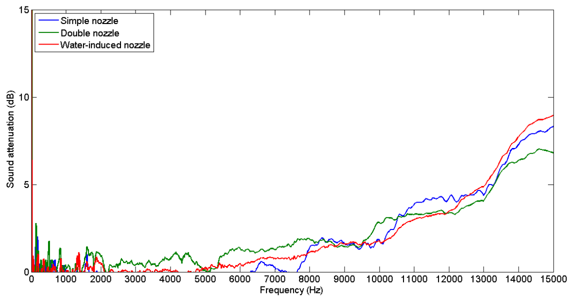

Figure 3. Sound attenuation using simple, double and water-induced nozzles.

The effect of type nozzle combination is now considered. Nozzle combination can give us partial information about the influence of heterogeneity. For this purpose, simple and water-induced nozzles are combined, resulting the homogeneity interruption due to the change of the water flow and the droplet size.

Two combinations have been proposed: water-induced + simple + water-induced, and simple + water-induced + simple. Results are given in Figure 4 (in order to compare the results, simple and water-induced attenuations independently have been included).

Using this nozzles combination, it is possible to see that, at frequencies below 6000 Hz, sound attenuation is very similar in all of them. This could be due to the reasons previously mentioned

Nevertheless, if we pay attention to the attenuation obtained at frequencies above 6000 Hz, the combination water-induced + simple + water-induced presents a higher global attenuation level with respect to the rest of configurations.

This nozzle combination gives a higher heterogeneity and, therefore, bigger differences between the mediums. Furthermore, droplets using water-induced nozzles contain small air bubbles inside, which could increase sound attenuation.

These results could be due to the combination of diverse phenomenon involved in sound attenuation by water, i.e. the influence of the water column thickness (at frequencies of 1700-1800 Hz), droplet size dispersion and, possibly, mass flow variations because of modifications in water flow.

Then, low and mid frequencies would be affected by the first phenomenon and higher frequencies would be affected by the other phenomenon.

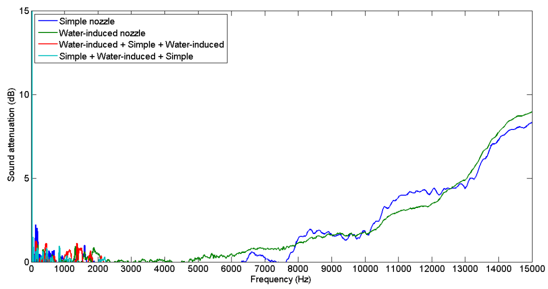

Figure 4. Sound attenuation using combined nozzles.

5. Conclusions

After the detailed analysis and discussion of the results obtained in the measurements, some conclusions can be extracted about the parameters studies.

For low and mid frequencies (from 1500 to 3500 Hz), the use of simple nozzles can be a good solution because these nozzles present the maximum attenuation level in this range. Nevertheless, the setting formed by simple + water-induced + simple nozzles is the one that present the better overall attenuation level

Water pressure is one of the parameters with most influence in sound attenuation. increasing pressure (and, therefore, flow), sound attenuation increases.

Different droplet size combination increases also attenuation and slightly larger droplets gives as a result a raise in sound attenuation.

Moreover, although it was not considered as a relevant parameter at the beginning of the work, water column thickness is a determinant factor to know the sound attenuation peak frequency, so it would be necessary a more intensive study about its influence.

This is a preliminary study about sound attenuation by gas-vapor-droplet suspensions. In order to determine, not only the parameters but also the physical mechanisms that influence in the sound attenuation, further work must be done.

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