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Wave Propagation in the Multilayered Low-pressure Near-space Atmosphere

Chao Li
State Key Laboratory of Acoustics
Institute of Acoustics Chinese Academy of Sciences
Beijing, China
lichao@mail.ioa.ac.cn

Hanyin Cui
State Key Laboratory of Acoustics
Institute of Acoustics Chinese Academy of Sciences
Beijing, China
cuihanyin@mail.ioa.ac.cn

Rushan Shen
University of Chinese Academy of Sciences
Institute of Acoustics Chinese Academy of Sciences
Beijing, China
shenrushan@mail.ioa.ac.cn

Xiaodong Peng
National Space Science Center
Chinese Academy of Sciences
Beijing, China
pxd@nssc.ac.cn

Xuchen Shen
National Space Science Center
Chinese Academy of Sciences
Beijing, China
shenxuchen@nssc.ac.cn

Yaqin Hou
Beijing Institute of Spacecraft Environment Engineering
Beijing, China
yaqin_306@163.com

Qinghua Gao
Beijing Institute of Spacecraft Environment Engineering
Beijing, China

Jing Wang
Beijing Institute of Spacecraft Environment Engineering
Beijing, China

Chun Liu
Beijing Institute of Spacecraft Environment Engineering
Beijing, China

Quan Guo
Institute of Crustal Dynamics Chinese Earthquake administration
Beijing, China

***Abstract*—The variation of sound speeds of air and nitrogen gas at temperatures from 15 to -80 ℃, and at gas pressures from 10^5 to 150 Pa have been measured in a KM2G space simulator. The objective is to provide the primary acoustic parameters to set up a proper multi-layered near-space atmosphere model, so that to simulate propagation paths of acoustic waves. From experimental data, sound speeds of both air and nitrogen gas decrease with the decreasing temperature from 15 to -80 ℃ and with the decreasing pressure from 10^5 to about 5000 Pa. However, sound speeds in the 15℃ rare air and nitrogen gas slightly increase with the dropping pressure below 5000 Pa, and this trend becomes more obviously when the temperature is low. This dispersion characteristic of acoustic wave in the near-space atmosphere should be considered during simulation of wave propagation.**

Keywords*—*sound speed, low pressure, dispersion, rarefied gas

I. Introduction

The near space refers to the region of the Earth's atmosphere from 20 to 100 km, which consists of the altitudes above where airlines fly but below orbiting satellites. This area has been used for high-altitude ballooning as the interest for scientific studies and communications. Infrasound signals, which are generated by earthquakes, lightning, or auroras, may propagate in the acoustic-waveguides of the near-space. We are interested to study the acoustic field in the near-space atmosphere, in order to better understand the infrasound signals measured by drifting balloon-borne sensors.

Both numerical and experimental investigations have been explored to understand the wave property in the near-space atmosphere. The pressure decreases with the increasing height, while the temperature varies greatly with height. At this stage, the sound speeds of acoustic waves are measured and analyzed in a medium-size space simulator. The pressures of the air and nitrogen gas in the vacuum chamber are adjusted from 10^5 to 150 Pa, respectively, and the temperature of nitrogen gas varies from 15 to -80 ℃, so that to simulate the low-pressure and low-temperature near-space atmosphere.

II. Experiments

Firstly, the variable pressure and temperature near-space atmosphere was reproduced using air and pure nitrogen gas, respectively, in a KM2G space simulator. The length and the inner diameter of this vacuum chamber are 3 m and 2 m, respectively. This medium-size simulator will reduce the chance of receiving reflection echoes from the chamber wall. The tested gases in the chamber are the room-temperature air and pure nitrogen gas, respectively. The temperatures of pure nitrogen gas are controlled to be around 15, 0, -20, -50, and -80℃ using the up-to-date cryogenic cooling system (down to -173℃), and the temperature evenness is smaller than 5℃. The gas pressure varies from 10^5 to 10^{-3} Pa, and the pressure precious is within ± 10 Pa.

Secondly, an acoustic measurement system was built-up in the space simulator, as shown in Fig. 1(a). Four pairs of piezo-transducers, with central frequencies being equal to 21, 25, 34, and 40 kHz, respectively, are placed in a specific designed flame, as illustrated in Fig. 1(b).

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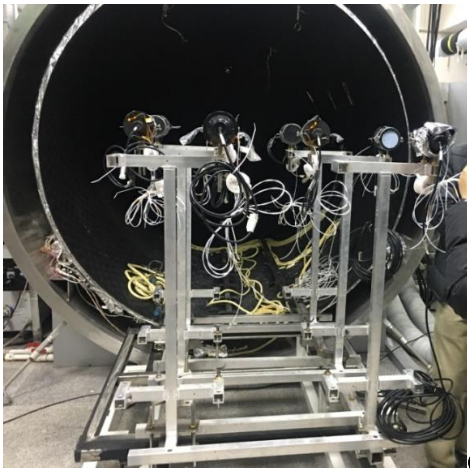
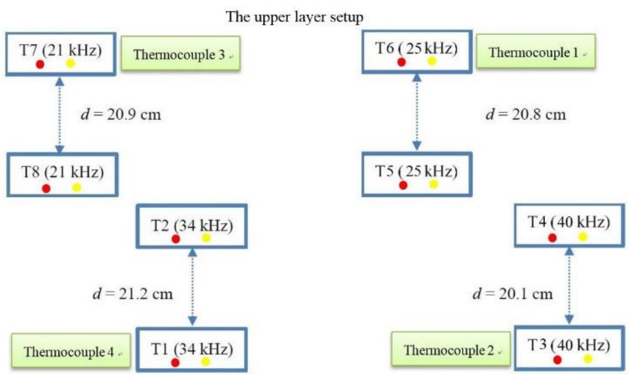


(a)



(b)

Fig. 1. The photo of the acoustic measurement system and the KM2G space simulator (a), the sketch of four-pair transducers.

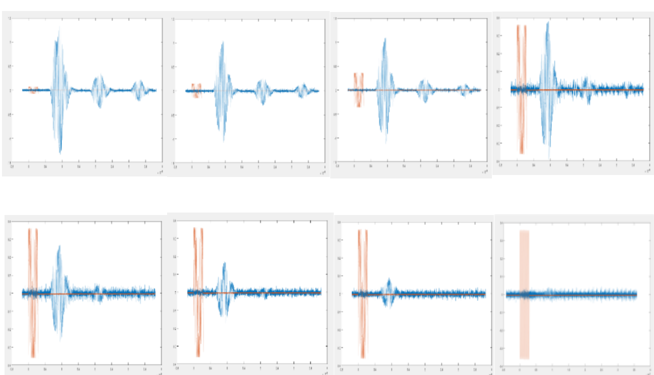


Fig. 2. The receiving signals of 34 kHz ultrasound waves with the air pressure being equal to 10^5, 10^4, 5000, 2000, 1500, 1000, 600, and 300 Pa, respectively.

All the transducers are covered by thin film heaters for heating, and adopted a temperature control system to control the transducer temperature to be around room temperature during the low-temperature tests. As illustrated in Fig. 1(b), four air thermocouples are measuring the real-time temperatures next to the four transducers. The pitch-catch technique has been applied to measure the sound speeds at different gas pressure and temperatures. Each pair of transducers are placed face to face, and the distance between the transmitter and receiver was set to be around 15, 20, and 25 cm, respectively.

III. Experimental Results and Analyses

A. The cross correlation method

The cross correlation technique has been applied to calculate the sound speeds of air and nitrogen gas at different temperatures and pressures. For instance, experimental results of receiving signals of 34 kHz ultrasound echoes propagating in the simulator filled with room temperature air, and the pressure in the chamber is dropping from 10^5 to 300 Pa, are given in Fig.2. The distance between two 34 kHz transducers is about 149.8 mm.

As shown in Fig.2, with the decreasing air pressure in the chamber, the amplitude of the receiving signal drops dramatically. When the pressure is above 5000 Pa, the receiving signals have relatively large signal to noise ratios and they have clearly second echoes and third echoes. For these cases, it is easy to directly obtain the travel times corresponding to the direct echo and the second echo, i.e., t_1 and t_2. And the speed of sound can be calculated from the equation

$$c = 2L/(t_2 - t_1), \tag{1}$$

where, L is the distance between the transmitter and the receiver. Compared to the method that using the travel time of the direct echo to get the sound speed, this second echo method could reduce the error from the acoustic-electrical signal transform time of a transducer, usually is about several μs.

We also applied the cross correlation method to calculate the sound speed. That is, the time-domain signals of the direct echo and the second echo are intercepted to be two independent signals with the same time intervals. And then, the time difference between the second and direct echoes can be obtained using the cross-correlation parameter. And by using (1), we could get the sound speed. For the case of the 15.4°C air at 10^5 Pa, we compared two sound speeds obtained using these two methods with the sound speed obtained using the idea gas assumption. And it is found that the cross-correlation method is more accurate, so that this method is chosen to process the other data.

As shown in Fig. 2, the signal to noise ratio of the receiving signal decreases with the decreasing pressure being lower than 2000 Pa. For example, we calculate the time difference, Δt ,between the direct echo at 2000 Pa and the direct echo at 10^5 Pa, and the sound speed at 2000 Pa air can be obtained from

$$c' = L\Big/\left(\frac{L}{c} + \Delta t\right), \tag{2}$$

B. Variation of sound speeds with decreasing gas-pressure

The experimental results of sound speed were compared with the theoretical sound-speed under the assumption that the room-temperature air and the -80-15°C pure nitrogen gas with pressures varying from 10^5 to 300 Pa are still ideal-gas. And the 21-40 kHz ultrasound waves are assumed to be adiabatic disturbances. With these assumptions, the sound speed can be calculated from

$$c = \sqrt{(\gamma(T,p)RT/M)}, \tag{3}$$

where T is the gas temperature in K, p is the gas pressure in Pa, R is the gas constant and it is equal to $8.31432\times10^{3}\,\mathrm{J(kmol)^{-1}K^{-1}}$, M is the molecular weight in $\mathrm{kg(kmol)^{-1}}$, and $\gamma(T,p)$ is the specific-heat ratio of the gas, which depends on the type of gas, the temperature, and the gas pressure.[1]

Firstly, the temperature effect on the ideal-gas sound-speed was considered. When the space simulator was filled with air, we only carried out experiments at different air pressures. The reason is that the moisture air will condensate at low-temperature. As shown in Fig. 3, the air temperature, recorded by the air thermal-couple, decreases from 15.4 to 13.8°C when the pressure drops from 10^5 to 300 Pa. The recorded air-temperature at each specific pressure is important to accurately estimate the theoretical sound speed.

Secondly, the effect of the varying specific ratio of heat at different temperatures and pressures on the ideal-gas sound-speed was also considered. From references[1,2], we could get the specific heat-ratio of air at 280K and 290K, and also that at 10^3, 10^4, 10^5 Pa, respectively. However, there is no record of specific heat-ratio of air below 10^3 Pa, which is the most interested parameter for our study. The specific heat-ratio of dry air at 280 K and 290 K and from 10^5 to 10^3 Pa, and also the estimated values at low pressures are given in Fig. 4.

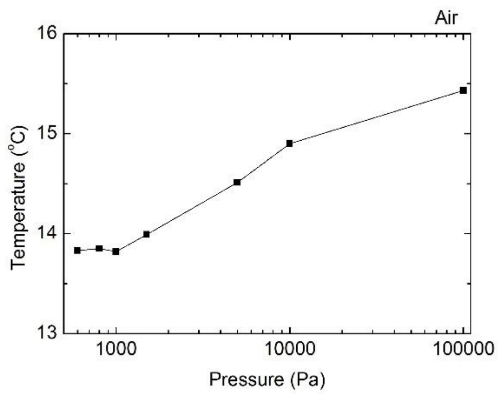


Fig. 3. The recorded air temperatures next to the 34 kHz transducer when the pressure in the simulator decreases from 10^5 to 300 Pa.

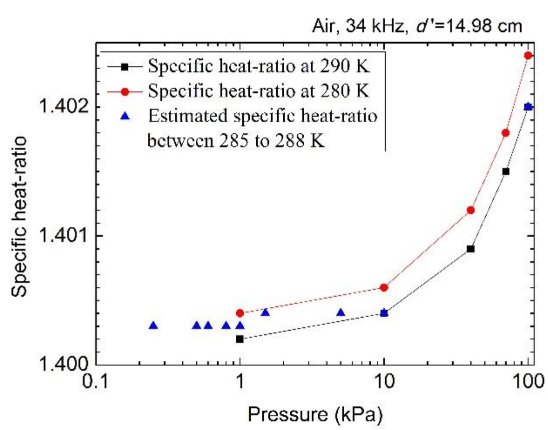


Fig. 4. The specific heat-ratios of air at temperatures from 280 to 290 K, and at pressures from 10^5 to 300 Pa.

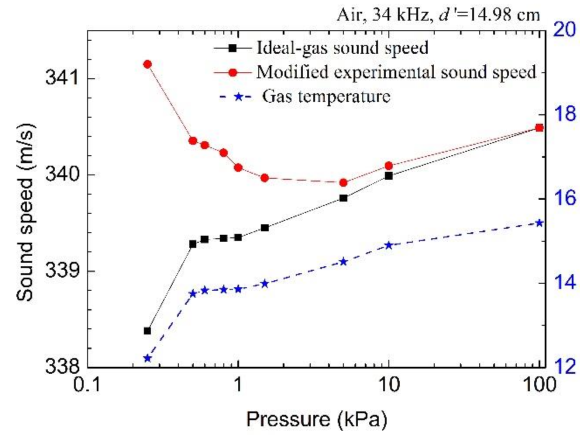


Fig. 5. Experimental measured sound speeds (red points) and idea-gas sound speeds (black squares) of air at different pressures. The temperature (blue stars) also decreases from 15.4 to 13.8°C with the decreasing pressure from 10^5 to 300 Pa.

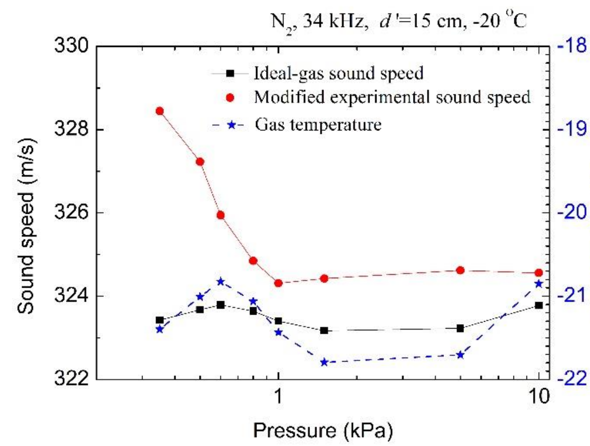


Fig.6 Experimental measured sound speeds (red points) and idea-gas sound speeds (black squares) of low-temperature pure nitrogen gas at different pressures. The gas temperature (blue stars) changes from -22 to -20°C from 10^4 to 350 Pa.

And then, the experimental and theoretical results of sound speeds of air at different pressures are shown in Fig. 5 for comparison. The air temperature decreases with the dropping pressure, and so does the ideal-gas sound-speed of air. As given in (3), temperature has the greatest effect on the speed. In Fig.5, the experimental sound speeds correlate well with the ideal-gas sound speeds when the pressure is above 5000 Pa. However, in the case of the air pressure is lower than 5000 Pa, the experimental sound speed of these low-density air increases with the decreasing pressure. And, the difference between the experimental and ideal-gas sound-speeds becomes larger with the decreasing pressure. This is similar to the dispersion phenomenon in a rarefied gas [3-5].

This dispersive phenomenon also appears in the low-pressure pure-nitrogen gas. For instance, the experimental and ideal-gas sound speeds of nitrogen gas at around -20°C temperatures and with varying pressures from 10^4 to 350 Pa are given in Fig.6. During this experiment, the gas-temperature in the chamber was controlled to be about -20°C using the liquid nitrogen temperature regulation system, while the recorded temperatures were slightly shifting within -2°C. As shown in Fig.6, the similar phenomenon that the experimental sound-speed of about -20°C nitrogen increases with decreasing pressure when the gas pressure is below 1000 Pa.

From the literatures [6,7], speeds of sound of nitrogen gas were measured at temperatures from 80 to 350K over a pressure range from 0.03 to 1.5 MPa. Their results show that speeds of sound increase with decreasing pressure when the temperature is lower than 150 K. When consider the dispersion in the rarefied gas, a decrease in pressure as the same result as a decrease in temperature and as the temperature decreases so does a more obviously dispersion.

IV. Conclusions

Speeds of sound for the room temperature air and -80 to 15°C varying-temperature pure gaseous-nitrogen have been measured over a pressure range from 10^5 to 150 Pa. The pitch-catch technique and the cross-correlation method have been used to obtain sound speeds. The experimental results and the ideal-gas sound speeds at different temperatures and pressure have been compared to investigate the dispersion characteristics of low-pressure air and that of the low-pressure low-temperature gaseous nitrogen. Further analyses will be carried out to study the dispersion in rarefied gas both theoretically and numerically.

Acknowledgment

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