Fluid loading effects for acoustical sensors in the atmospheres of Mars, Venus, Titan, and Jupiter

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Abstract: This paper shows that corrections for fluid loading must be undertaken to Earth-based calibrations for planetary probe sensors, which rely on accurate and precise predictions of mechanical vibrations. These sensors include acoustical instrumentation, and sensors for the mass change resulting from species accumulation upon oscillating plates. Some published designs are particularly susceptible (an example leading to around an octave error in the frequency calibration for Venus is shown). Because such corrections have not previously been raised, and would be almost impossible to incorporate into drop tests of probes, this paper demonstrates the surprising results of applying well-established formulations.

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1. Introduction

Only a handful of probes sent to other worlds have been equipped with instrumentation for recording extraterrestrial soundscapes.[1] Of those, only two[2–7] have returned data, and in both cases the passive acoustic data were dominated by wind noise, the pressure fluctuations caused by flow over the microphone surface (although active acoustics worked very well on the *Huygens* mission[4–7]). Greater chances of success in recording an alien soundscape require that probe designers take full account of acoustical capabilities, which, though established on Earth, require care in transposition to other worlds. Some solutions are so well-established that their basis can be found in commercial products (for example, the use of windshields or multiple microphones to distinguish acoustic signals from aerodynamic noise). In other cases, it is the esoteric nature of the alien world itself, which will bring into play unexpected acoustical phenomena. An example of the latter (fluid loading of structures) is explained in this paper, with specific attention to the effect of other worlds on acoustical sensors. Fluid loading is a well-established phenomenon, and this paper does not introduce new physics. Rather it undertakes calculations using established formulas to demonstrate that fluid loading on some planets will cause significant deviation in the performance of acoustical sensors of certain geometries, if that performance is calibrated on Earth and not corrected for fluid loading.

It is well-known that whenever a solid structure vibrates in an atmosphere, the gas, which is set into motion by the structural vibration, contributes to the inertia and damping associated with that oscillation. This usually increases both compared to the *in vacuo* characteristics of the vibrating component, but since Earth's atmosphere is denser than that of Mars, both are usually reduced when a structure is transposed from ground level on Earth to Mars. Both are, however, increased when structures are transposed from ground level on Earth to ground level in the denser atmospheres of Venus and Titan. From the viewpoint of the design of acoustical sensors for planetary probes, the importance of this lies in the fact that (i) the characteristics of a vibrating structure on Earth are sometimes taken to be intrinsic, which is to confuse them with the *in vacuo* characteristics; (ii) inclusion of the effect of dense atmospheres is commonplace in some areas of planetary probe design (such as parachutes or dirigibles, the effect of turbulence, etc.), but the effect of fluid loading in changing the natural frequency and damping of structures is less common; (iii) such effects will not be included in many Earth-based calibrations and tests, e.g., a drop test of a probe through Earth's atmosphere; and (iv) the effects are greatest on light, stiff structures, such as are common on planetary probes. These issues are particularly germane for acoustical sources and sensors (e.g., anemometers, sensors for atmospheric sound speed and dissipation, and microphones for probes and suits). This is especially the case when the sensors are not in free space, but embedded within tubes, a feature which has appeared in several designs for acoustical instrumentation for planetary probes.

There is a range of acoustical measurements, which may be undertaken to determine the properties of planetary atmospheres.[8] Currently there is considerable interest in acoustic anemometry, and the measurement of atmospheric dissipation, sound speed, and soundscapes.[8–11] Since the earliest proposals,[12,13] many designs mount acoustic transmitters and receivers in tubes or sample vessels in order to infer the properties of planetary gases through acoustical measurements[14] or acousto-optical methods[15] or flow excitation of the natural frequency of a gas-filled vessel.[8] Encapsulating the gas in an enclosure for measurement has many attractions: For example, it allows the gas temperature to be controlled, so that the sound speed can, given other constraints, be inverted to obtain the gas composition.[8] Perhaps the earliest reference[12] states the following: "The velocity of sound in a gas c is a function of T [temperature], M [molecular weight], and γ [specific heat ratio], and is given by $c^2=\gamma RT/M$, where R is the gas constant. This well-known relation has been used in the past in various techniques to measure the temperature $[T]$ of Earth's atmosphere, where M and γ were accurately known. It is proposed to reverse this method and bring a volume of the atmosphere of Venus into a thermostatically controlled tube where the temperature is known accurately and to determine M/γ by measuring the velocity of sound through the medium in the tube." Many of those proposing such acoustical instruments emphasize the need for the use of accurately preset frequencies and amplitudes, and while such geometries would not incur significant fluid loading in low-density atmospheres, they have been proposed for deployment on Venus, or Jupiter, and the planets beyond. For example, for a Venus probe Hanel and Strange[13] wrote the following: "The wave propagation in the unknown gas mixture is contained in a narrow channel that was cut in spiral form in a solid aluminum disk as shown in [their] Fig. 3. A small sonic transducer at the center of the disk generates a sound wave of constant amplitude, with a constant and precisely known audio frequency. Two identical condenser microphones, separated by several wavelengths, form part of the tube wall." This design, established in the 1960s, is still in current proposals in various forms, for example, in the design of a probe to the Jovian planets (Jupiter, Saturn, Uranus, and Neptune).[14] When sampling low-density fluids, radiation mass is not an issue, but when sampling dense gases or liquids,[16] then a range of acoustical phenomena, such as fluid loading and the coupling between the fluid and the walls, can become important. In addition to acoustical sensors, this can affect others that rely on mechanical vibration, for example, those which respond with high sensitivity to changes in the inertia or stiffness associated with vibrating surfaces as, for example, species accumulate upon an oscillating plate.[17]

This paper calculates the inertial effect of fluid loading at ground level on Venus, Mars, Titan, and at two locations in the atmosphere of Jupiter, on a range of structures, showing that the above designs, which mount sensors in tubes, will incur significant fluid loading.

2. Method

It is well-known that the force that drives a structure to vibrate in a gas encounters a mechanical impedance (Z_m+Z_r), which differs from the *in vacuo* input mechanical impedance (Z_m) because of the contribution of the radiation impedance $(Z_r=R_r+jX_r)$. The real component of Z_r is well-known as the radiation resistance, R_r, a positive value of which indicates an additional power dissipation by the source as a result of the presence of the fluid. The imaginary component of Z_r is the radiation reactance, X_r, a positive value of which indicates increased mass loading caused by the presence of the fluid. The inertia $(m+m_r)$ associated with the immersed oscillation differs from the *in vacuo* value m by the "radiation mass" $m_r=X_r/\omega$. If $m_r>0$ then for an oscillator of stiffness s the resonance frequency of the source is reduced from the *in vacuo* value f_0

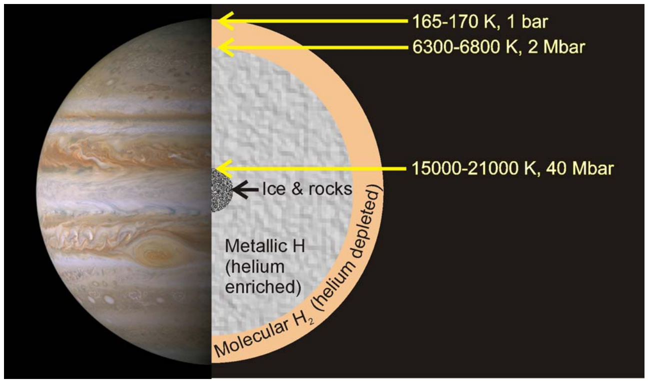

Fig. 1. (Color online) A schematic of the interior of Jupiter. The photographic elements of the image are credited to NASA, ESA, and the Hubble Heritage Team (AURA/STScI). The diagram indicates the pressures, temperatures, and composition of layers. The two points for which calculations are undertaken in the paper (close to the 1 bar level) are indistinguishable from one another on this scale (Ref. 28).

$=(1/2\pi)\sqrt{s/m}$ to the fluid loaded value $f_{\text{atm}}=(1/2\pi)\sqrt{s/(m+m_r)}$, a change in $\Delta f/f_0=(f_{\text{atm}}-f_0)/f_0=(\sqrt{m/(m+m_r)}-1)$, which tends to $-m_r/2m$ if $|m_r|\ll|m|$.

The effect of fluid loading on the natural frequencies of two versions of each of the following objects will be estimated for extraterrestrial locations: (i) a hollow steel sphere of outer radius $a=10$ cm ringing with spherical symmetry; (ii) a piston in a short pipe of length l, which opens out to the atmosphere through a hole in a plate (the hole having the same radius d as the pipe); and (iii) a length l of an infinite uniformly vibrating wire (of radius b). Assuming acoustically rigid structures and in the long wavelength limit ($ka\ll 1$, $kd<kl\ll 1$, and $kb\ll 1$ for wavenumber k), the radiation impedances of all these structure are primarily imaginary, such that the reactance dominates and the respective radiation masses equal: (i) $m_{r,\text{sphere}}\approx 4\pi a^3\rho$, (ii) $m_{r,\text{pipe}}\approx\rho\pi d^2 l+8\rho\pi d^3/(3\pi)$, and (iii) $m_{r,\text{wire}}\approx\rho\pi b^2 l$.[18–20] The same principle can be applied to other geometries[21–23] and when the wavelength is not much larger than the structure (the Huygens sound speed sensor used 1 MHz), although the expressions are more complicated.

Recognizing that conditions (e.g., temperature T and static pressure P) can vary at a given altitude on a given world, the added mass depends primarily on the atmospheric density, ρ. The following nominal values are used for ρ for the atmospheres of Earth ($\rho=1.3$ kg m^{-3}), Mars ($\rho=0.02$ kg m^{-3}, with $T=220$ K, $P=0.007$ bar, and compositions of 95% CO_2, 2.7% N_2, and 300 ppm H_2O), Venus ($\rho=65$ kg m^{-3}, with $T=730$ K, $P=90$ bar, and compositions of 3.5% N_2 and 96% CO_2), and Titan ($\rho=5.5$ kg m^{-3}, with $T=95$ K, $P=1.6$ bar, and compositions of 95% N_2 and 5% CH_4).[24] These correspond to ground level averages since exploration by a lander is not atypical for these worlds.

Other candidate planets will require atmospheric probes. The upper atmospheres of Jupiter and Saturn are 90% hydrogen with ~10% helium and trace amounts of other compounds. Uranus and Neptune, in comparison, contain less hydrogen and helium, and more oxygen, carbon, nitrogen, and sulfur. Jupiter has a dense core of uncertain composition but probable existence,[25] surrounded by a 40 000-km-thick layer of liquid metallic hydrogen and some helium, which extends out to about 78% of the radius of the planet[26,27] (Fig. 1). At the top of this layer of liquid metallic hydrogen the temperature is 10 000 K and the pressure is 200 GPa. Droplets resembling rain of helium and neon precipitate down through the metallic hydrogen layer, depleting the abundance of helium and neon in the upper atmosphere.[28] Above the metallic hydrogen is a 21 000-km-thick layer of liquid hydrogen and gaseous hydrogen, with no sharp boundary between the two, called the interior atmosphere. The clouds (primarily of crystalline ammonia, ammonia hydrosulfide, and water) exist at the top of the atmosphere, in a layer that is around 50 km thick, where the atmospheric pressure is 20–200 kPa.

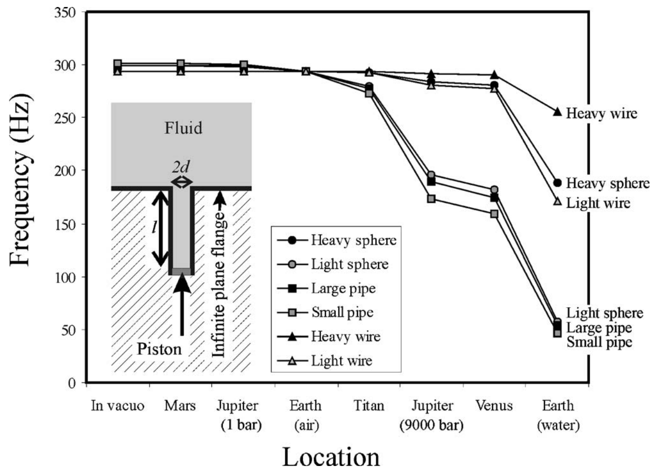

Fig. 2. The resulting natural frequency when added mass is included, for two hollow steel spheres with outer radii $a=10$ cm and wall thicknesses of 1 cm (a "heavy sphere" containing 8.74 kg of steel) and 0.5 mm (a "light sphere" of 0.48 kg steel). Ground-level atmospheres on Earth, Venus, Mars, and Titan, plus two locations on Jupiter, are used, with immersion in water at Earth's surface shown for comparison (a location that could be used for ground-truthing predictions). Predictions are also shown for two short pipes, open to the atmosphere, containing pistons (the large pipe has a length of 18 cm, diameter of 2 cm, and, at its base, contains a piston of mass 2 g; the short pipe has a length of 10 cm, diameter of 1.5 cm, and at its base contains a piston of mass 0.5 g). Predictions are shown for two wires, a heavy wire (10^{-2} kg/m, 1 mm radius) and a light wire (10^{-4} kg/m, 0.25 mm radius). The inset shows the geometry for the piston-driven pipe discussed in the text [which could represent a biomimetic sound source (e.g., vocal tract) or sensor (ear canal), or a component of a sampling device].

Calculations are made for two locations of possible interest for future probes to Jupiter: (i) at an equatorial radius of 71 492 km from Jupiter's center, where $P=1$ bar (105 Pa), $\rho=0.1$ kg m^{-3}, and $T\sim 165$ K;[29] and (ii) the estimated maximum operational penetration depth of some future very robust probe. Extrapolating from current terrestrial seismic sensors,[30] $P=0.9$ GPa would set a limit beyond the capability of such a sensor, and provide a useful point for comparison (see later). This pressure occurs 6.96×10^7 m from Jupiter's center, where $T\sim 2000$ K and $\rho\sim 50$ kg m^{-3}.[31]

3. Results

For comparative purposes, the artificial assumption is made that all the objects are tuned to vibrate at ground level on Earth at 293.66 Hz (the pitch of the note D) which, because the fluid loading on Earth differs across the range of objects tested, gives them different *in vacuo* frequencies (Fig. 2). Figure 2 shows to what extent fluid loading, taken in isolation to other effects (e.g., sound speed variations), changes the pitch for two versions of the different shapes (i)–(iii) described in Sec. 2 (details are given in the caption).

The choice of the altitude on Jupiter where the static pressure equals 0.9 GPa can now be seen in context, since although it represents an environment beyond the likely reach of near-future probes, from Fig. 2 the fluid loading there is less than that which instruments of the same geometry on Venus would experience. The effect is significant for some geometries: For example, the natural frequency of the piston-driven pipe on Earth is around twice the value it would have on Venus (a location to which acoustical sensors have already been sent[2,3]). The effect is smaller on Mars and of the opposite sign.

The magnitude of the effect depends primarily on two key parameters. For each structure, the one with the smaller volume-averaged density is more affected by fluid loading. This is because the first key parameter is the "buoyancy," the ratio of the mass of the structure to the mass of fluid it displaces when stationary [since the radiation mass is related to the latter, and (m/m_r) determines the value of $\Delta f/f_0$]. The second key parameter concerns the geometrical constraints, which determine how much of the atmosphere is set into motion when the oscillation occurs. Of the three structures, the wire causes primarily local fluid motion in a dipolelike manner, whereas the sphere is assumed to act as a monopole source of atmospheric motion, such the fluid velocity falls off to first order as an inverse square law from the fluid wall. The pipe, however, entrains a body of air to move in a one-dimensional manner, the fluid velocity not falling off with distance from the piston until outside of the pipe, giving it the greatest fluid loading of the three.

4. Discussion

The above calculations illustrate the effect of fluid loading, which can affect both the inertia and dissipation associated with the motion of a structure. It is important to stress that the fluid loading has been treated in isolation to other effects, which can influence the frequency responses of structures, such as the effect of thermal expansion on stiffness. In the specific case of sound sources, some sources are particularly affected by the atmospheric sound speed (such as organ pipes). It is interesting to note that the pitch of an organ pipe will increase on Venus compared to Earth, because the sound speed in the atmosphere there is greater than that on Earth, but that the pitch of the human voice (were it to be made operable on Venus) will decrease because there fluid loading, not the sound speed, is the dominant effect (see Ref. 32; the pipes used above roughly model the human adult and child vocal tract, and the two wires correspond to the dimensions and masses of heavy and light guitar strings).

Probe structures are lightweight where possible, so that (depending on the geometry) fluid loading could have significant effects on Venus and the outer planets, and make Earth-based calibrations incorrect. While the effect is smaller on other worlds, sensitive instrumentation based on monitoring of mechanical resonances[17] should account for the alien fluid loading when transposing Earth-based calibrations. Given the constraints for conserving power yet obtaining good signal-to-noise ratios, active acoustic sensors are often narrowband. Where fluid structure interaction is significant (for example, in coupling between fluid and container walls[33]), the frequency characteristics and dissipation of the fluid in the sample tube will differ from those found in the bulk atmosphere. Account must be taken of these effects when acoustic sensors are used in the dense atmospheres of other worlds.

5. Conclusion

This paper has outlined how fluid loading can affect the dissipation and inertia associated with the motion of a structure, and shown that, at least for Venus, the effects can be considerable, depending on the geometry and density of the structure. Fluid loading calculations should be undertaken for future acoustic systems on Venus and Titan.

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