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ガスジェット浮遊中の溶融金属液滴の表面振動特性の数値解析法

Numerical analysis method for oscillation behavior of aerodynamically levitated molten metal droplets

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1. Introduction

For sustainable manned activities on the moon, manufacturing with lunar regolith is essential. Especially, the melting and solidification process is necessary for the exterior walls so that they can survive in the severe lunar environment. For this purpose, preliminary numerical simulations play significant roles in the design of efficient manufacturing processes. Although the main components of the lunar regolith are metal oxides, the thermophysical properties of molten metal oxides have been measured for only a few materials. Therefore, the measurements of the thermophysical properties of molten metal oxides are an important task. For such measurements, aerodynamic levitation (ADL) is regarded as a suitable method, but there is an uncertainty problem. **Figure 1**(a) shows the appearance of droplet during ADL.

In ADL, the oscillatory behavior of a droplet is observed with a camera, and surface tension and viscosity are calculated based on mathematical models using the obtained frequency and damping time constant. The relationship between frequency and surface tension was analytically derived by Rayleigh[1)], and the relationship between the damping time constant and viscosity was derived by Lamb[2)]. In these mathematical models, it is assumed that the droplet is a sphere, and that the system is in a stationary state on a time-averaged basis. In ADL, internal convection occurs due to the Marangoni effect from heating the droplet and the shear force from the airflow. This convection is thought to alter the frequency and damping time constant, which is believed to be the cause of the discrepancies. This study is aimed to establish the relationship between physical properties (surface tension and viscosity) and oscillation behavior (frequency and decay time constant).

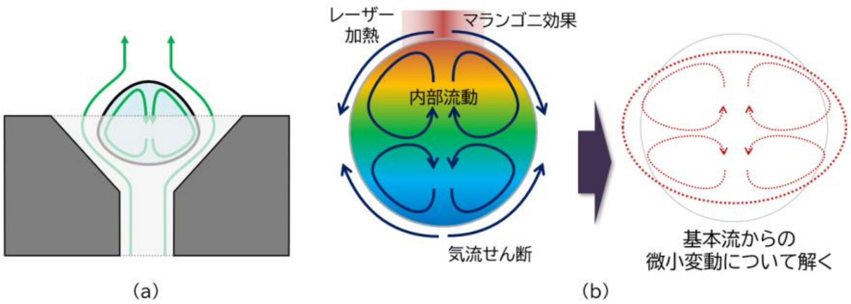

Fig. 1: (a) Schematics of aero-dynamic levitation. (b) Problems to be considered

2. Approach

Basic concept

On the surface of a droplet levitated by a gas jet, aerodynamic forces from the airflow and thermal flow due to laser heating occur. The pressure on the normal droplet surface is determined by the balance between Laplace pressure due to curvature distribution and hydrostatic pressure, to which pressure from the gas jet is added. The shear forces acting on the liquid surface include not only the shear force from the airflow but also the Marangoni effect caused by the surface temperature distribution formed by laser heating. These shear forces generate internal flow. Constructing a model that considers all these factors is complex; therefore, this study ignores the static deformation of the droplet. Although the deformation of the droplet would dynamically change the gas jet pressure and shear forces, these are also disregarded for simplicity.

The overall structure of the calculation model, which shown in **Figure 1**(b), involves decomposing the flow field into a basic flow, assuming an axisymmetric steady state, and fluctuation components from the basic flow. The basic flow is calculated as a nonlinear problem. The fluctuation components, being assumed small, are linearized, and an eigenvalue problem concerning the fluctuation field is solved to determine the oscillation frequencies and damping time constants.

Mathematical model of surface vibration

The droplet is assumed to be axisymmetric with respect to the direction of gravity. The interface position of the droplet is implicit function representation as shown in equation (1).

$$F(r,\theta,\varphi,t) = r - R_0\big(1 + r'(\theta,\varphi,t)\big), \tag{1}$$

where R_0 is the radius of the corresponding sphere, and r' is the relative deformation from the perfect sphere. The flow field is divided into a basic flow and oscillatory components and is expressed in spherical coordinates as shown in equation (2).

$$\begin{cases} \boldsymbol{u}(r,\theta,\varphi,t) = \boldsymbol{u_0}(r,\theta) + \boldsymbol{u}'(r,\theta,\varphi,t) \\ \boldsymbol{p}(r,\theta,\varphi,t) = \boldsymbol{p_0}(r,\theta) + \boldsymbol{p}'(r,\theta,\varphi,t) \\ \boldsymbol{\Theta}(r,\theta,\varphi,t) = \boldsymbol{\Theta_0}(r,\theta) + \boldsymbol{\Theta}'(r,\theta,\varphi,t) \end{cases}, \tag{2}$$

For spatial discretization, the spectral method is used, expanding as shown in equation (3).

$$u(r,\theta,\varphi) = \sum_{i}^{N_r}\sum_{l=o}^{N_l}\sum_{m=-l}^{l} u_{ilm}(t)T_i(r)Y_l^m(\theta,\varphi)\,, \tag{3}$$

In the r direction, Chebyshev polynomials are used, and in the θ and ϕ directions, spherical harmonics are used as basis functions. For the discretized equations, the basic flow is computed iteratively using the Newton-Raphson method. Assuming the following normal modes in equation (4) for the linearized perturbation equations, they are solved as a generalized complex eigenvalue problem.

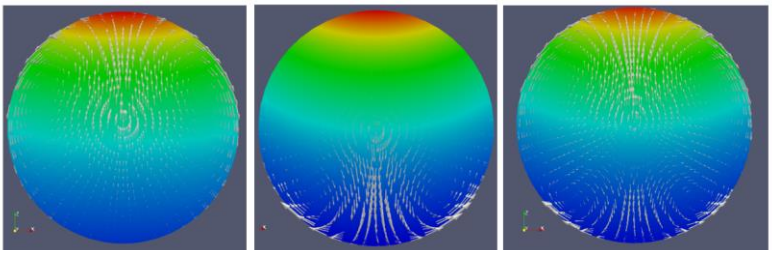

Fig.2: Surface oscillation and disturbance velocity fields.

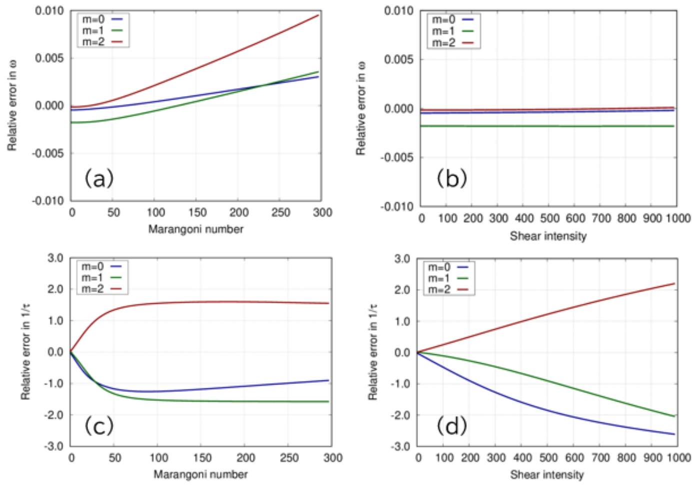

Fig.3: (a,b) Relative errors in oscillation frequencies from Rayleigh's frequency. (c,d) Relative errors in time constant for decay from Lamb's theory.

$$\begin{pmatrix} \boldsymbol{u}'(r,\theta,\varphi,t) \\ p'(r,\theta,\varphi,t) \\ \Theta'(r,\theta,\varphi,t) \end{pmatrix} = \begin{pmatrix} \hat{\boldsymbol{u}}(r,\theta) \\ \hat{p}(r,\theta) \\ \hat{\Theta}(r,\theta) \end{pmatrix} \exp(\lambda t + im\varphi) + \mathrm{c.c.}, \tag{4}$$

Solving the eigenvalue problem yields the decay time constant τ and the frequency ω.

3. Results

Fig.3: (a,b) Relative errors in oscillation frequencies from Rayleigh's frequency. (c,d) Relative errors in time constant for decay from Lamb's theory. We performed numerical simulations assuming a gas jet levitation experiment of molten Ni. **Fig.2** shows the dynamic deformation of the droplet obtained as eigenvectors, with pressure (color) and velocity (vectors) of the disturbance field. **Fig.3** shows the oscillation frequency (a, b) and decay time constant (c, d) when varying the range of the Marangoni effect and the strength of airflow shear, displayed as the relative error from the Rayleigh oscillation frequency and Lamb's decay time constant. For both the Marangoni effect and airflow shear, there was little change observed in the vibration frequency. However, the damping time constant showed different trends depending on the azimuthal wavenumber m. The $m = 0$ and $m = 1$ modes exhibited a decreasing trend, while the $m = 2$ mode showed an increasing trend. When combining all modes, the overall damping tended to accelerate, which is qualitatively consistent with the trends observed on the ISS(3).

Acknowledgments

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References

1) L. Rayleigh: Phil. Mag. 32, pp. 529–546 (1916).
2) H. Lamb: Hydrodynamics, 6th ed. Cambridge University Press (1932)
3) T. Ishikawa et al.: Int. J. Microgravity Sci. Appl. 39(1), p.390101 (2022).