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Influence of Mechanical Vibration on Cavity Enhanced Absorption Spectroscopy

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The influence of mechanical vibration on Cavity Enhanced Absorption Spectroscopy was investigated experimentally. Absorption lines of ArI at 772.38 nm and 772.42 nm in a microwave discharge cell (100W, 2kPa) were targeted. In order to investigate the influence of mechanical vibration on CEAS, the high-reflectance mirror for constructing a cavity was placed on a traverse stage and vibrated axially and vertically. The resonated laser intensities were more stable with the vertical vibration than those with the horizontal vibration. In order to improve the fluctuation of the transmitted laser intensity, rapid sweep on CEAS was tried. As the sweep frequency increased, high order modes were suppressed and TEM_{00} mode was dominant. While when the laser frequency was sweep rapidly, the transmitted laser intensity became smaller and the emission ratio from the plasma became larger. As a result, absorbance was underestimated with 5,000GHz/s.

I. Introduction

When a spacecrafts enters into the atmosphere of the Earth or other planets with a very high speed, a strong detached shock wave is formed around the spacecraft. This makes it necessary to use thermal protection systems (TPS) to prevent the destruction of the space vehicle. High enthalpy flow generators have been developed to simulate the aeroheating environment atmospheric entry for testing the TPS performance since the late 1950s [1]. In these facilities, segmented Arc heated wind tunnel has been widely used because of their wide range conditions. In this facility, the flow accelerates, the density and collision rates fall rapidly, and the stream is left in a state of thermal and chemical nonequilibrium before it reaches the nozzle exit. Therefore, it is useful to measure the chemical composition and enthalpy in these plumes for the evaluation of TPS, as well as for the validation of CFD models of non-equilibrium flows. Laser-induced fluorescence is an optical diagnostic method that yields space and time resolved populations, in particular of atomic ground states in plasma [2]. Our research group also has been applied two-photon LIF for evaluating the number density of atomic oxygen [3] and nitrogen [4] to the 750 kW arc heated wind tunnel in JAXA. However, the measurement accuracy of translational temperature is low because of the wide laser linewidth. Comparing with LIF, laser absorption spectroscopy (LAS) has high measurement accuracy when we use narrow-linewidth laser, such as a laser diode with an external cavity.

In our previous study, LAS has been applied to the plumes of a constricted arc heated wind tunnel [5] and an inductively coupled plasma generator [6], and the number density of meta-stable atomic oxygen and translational temperature were measured. In these measurement, strong absorption signals of the OI at 777.19 nm line were observed in oxygen or argon/oxygen flows. Then the number density OI at absorbing state $3s^5S$ was estimated as 3 x 10^{15} – 3 x $10^{17} m^{-3}$. While, in a nitrogen/oxygen flow, the OI ($3s^5S$) number density was lower than the detectable limit of 3 x 10^{15} (fractional absorption of 1%) [7]. This would be because large part of input energy was consumed

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in nitrogen dissociation, resulting in lower electron temperature. In another attempt of LAS undertaken in the NASA Ames interaction heating facility (60MW) arc wind tunnel, Kim et al. succeeded in the measurements of absorption of atomic oxygen and nitrogen in the arc heater region upstream of the nozzle throat, whereas they have not yet detected the absorption signal within its plume downstream of the nozzle expansion [8].

Recently, Cavity Enhanced Absorption Spectroscopy (CEAS), which is one of the cavity-based absorption methods, was applied to an arc wind-tunnel flow to measure the temperature distributions [9]. Consequently, sensitivity was improved by more than 2 orders of magnitude compared with conventional single-pass laser absorption spectroscopy. The temperature distribution of 0.2 % diluted oxygen estimated by CEAS shows a good agreement with that of argon estimated by single-pass LAS.

When CEAS is applied to a large scale arcjet and ICP facility, the transmitted laser intensity would be fluctuated by the mechanical vibration from the vacuum pump, the cooling water system, and so on as shown in Fig.1. When the vacuum pump and the cooling water system turned on, sideband signals became large and the maximum intensity in the transmitted laser intensity with the resonance did not have same value. In addition, the free spectral range of the cavity changed. Because of these fluctuations, the absorption signal could not be obtained in the 750kW segmented Arc heated wind tunnel developed in JAXA Chofu space center. In order to investigate the influence of the mechanical vibration on CEAS, intentional vibrations are added to the cavity mirror and the sensitivities are compared with each other.

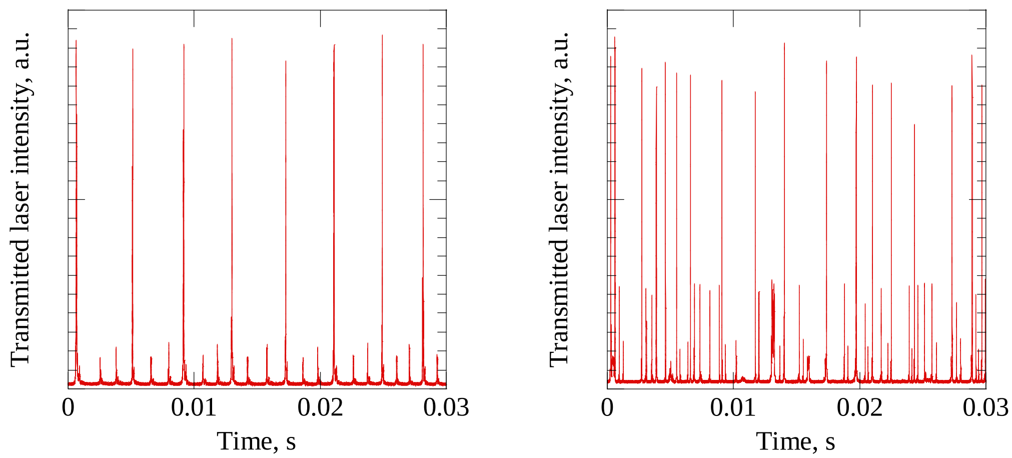


Fig.1 Transmitted laser intensity through the cavity without (left) and with (right) the working of the vacuum pump and cooling water

II. Theory

A. Laser Absorption Spectroscopy

The intensity variation dI of a laser beam with intensity I propagating in the x direction through an absorbing medium, is expressed as follows,

$$\mathrm{d}I = -k_\nu I_0 \mathrm{d}x \,. \tag{1}$$

The k_ν is the function of the laser frequency ν and expressed in the following Voigt profile

$$k_\nu = K \frac{2}{\Delta\nu_\mathrm{D}} \sqrt{\frac{\ln 2}{\pi}} \int_{-\infty}^{\infty} \frac{\exp\left(-t^2\right)}{y^2 + (x-t)^2} \mathrm{d}t$$
$$x = \frac{\sqrt{\ln 2}\left(\nu - \nu_0\right)}{\Delta\nu_\mathrm{D}} \tag{2}$$
$$y = \frac{\sqrt{\ln 2}\,\Delta\nu_\mathrm{L}}{\Delta\nu_\mathrm{D}}$$

Number density of absorption state n_i is related to the integrated absorption coefficient K as,[16]

$$K \equiv \int_{-\infty}^{\infty} k_\nu d\nu \approx \frac{\lambda_0^{\ 2}}{8\pi} \frac{g_j}{g_i} A_{ji} n_i \cdot \quad (3)$$

And the translational temperature is related to the Doppler width as follows.

$$T_{tr} = \frac{c^2 \cdot (\Delta\nu_{\mathrm{D}})^2 M_{\mathrm{A}}}{8 \ln 2 \cdot k \nu_0^{\ 2}} \cdot \quad (4)$$

B. Cavity Enhanced Absorption Spectroscopy

For CEAS, a Fabry-Perot cavity is constructed using two high-reflectance mirrors. The transmitted laser intensity is calculated using the following Fabry-Perot equation:

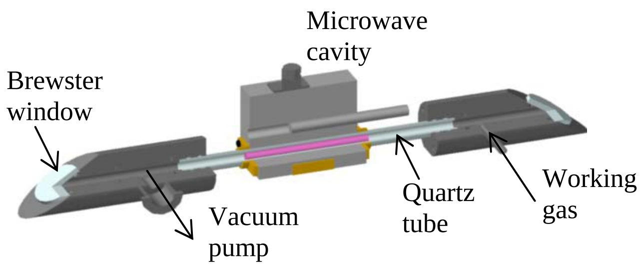
$$\frac{I_t}{I_0} = \frac{T_1 T_2 \exp(-kd_0)}{\{1 - R_{\mathrm{eff}} \exp(-kd_0)\}^2} \,. \quad (5)$$

The resonant condition and the losses in the cavity would affect the transmitted laser intensity. Therefore, the effective reflectance R_{eff} is introduced to denote the reflectance of the mirrors. From Eq. (5), the relation between the absorbance in single-pass LAS kd_0 and that in CEAS kd_{CEAS} is obtained as follows:

$$kd_{\mathrm{CEAS}} = -\ln\left(\frac{I_t}{I_0}\right)_{CEAS} = -\ln\left[\frac{(1 - R_{\mathrm{eff}})^2 \exp(-kd_0)}{\{1 - R_{\mathrm{eff}} \exp(-kd_0)\}^2}\right]. \quad (5)$$

III. Experimental Setup

A schematic diagram of the measurement system for CEAS is illustrated in Fig.1. A tunable diode-laser with an external cavity (velocity model 6300, New Focus Inc.) was used as the laser oscillator. It is not accompanied with mode-hops in wide modulation width, achieving the stable measurements. The laser frequency was modulated over about 40GHz at approximately a 0.5 Hz repetition frequency by a function generator. High-reflectance concave mirrors with a 1.5-m-curvature radius (Layertec) were used for constructing a cavity. In this study, *d* was fixed to be 0.5m (its free spectral range is 300 MHz). In order to vibrate the reflectance mirrors, they were placed on a translation stage (NF15AP25/M, Thorlabs INC). A faraday optical isolator was inserted between the tunable diode laser and the optics to reduce optical feedback to the laser diode. An etalon with a 0.75 GHz FSR was used to measure the frequency-modulation width. Emission from the plasma was shielded by a bandpass filter, the center wavelength and full width at half maximum of which are 10 nm, respectively. The transmitted laser intensity was measured by a photo multiplier tube (H8249-102, Hamamatsu Photonics KK). To apply A/D conversion and quick storage, a peripheral component interconnect digitizer (DP306, Agilent Technologies) with 12-bit resolution was used. This apparatus allows us to store 100 megasample data. In this research, the absorption lines of ArI at 772.38 nm ($4s^2[3/2] \rightarrow 4p^2[3/2]$) and 772.42 nm ($4s^2[1/2] \rightarrow 4p^2[1/2]$) were used. The transition data of these lines are shown in Table 1. An argon glow discharge tube was used to know the center absorption frequency. Its input power, discharge voltage and pressure were 2.0 W, 400 V and 80 Pa, respectively. In CEAS, energy losses in the cavity due to optical windows degrade the signal-to-noise ratio. To minimize such effects, Brewster windows and a polarization controller (FPC030, Thorlabs, Inc.) were introduced. The incident laser at the Brewster angle transmits the window without energy losses [10].



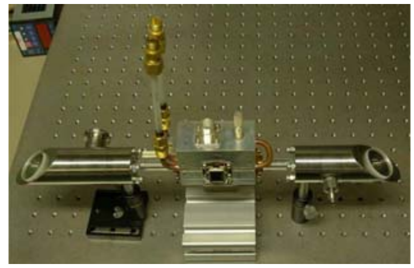


Fig.3 The schematic of the microwave discharge cell (left) and its photograph (right)

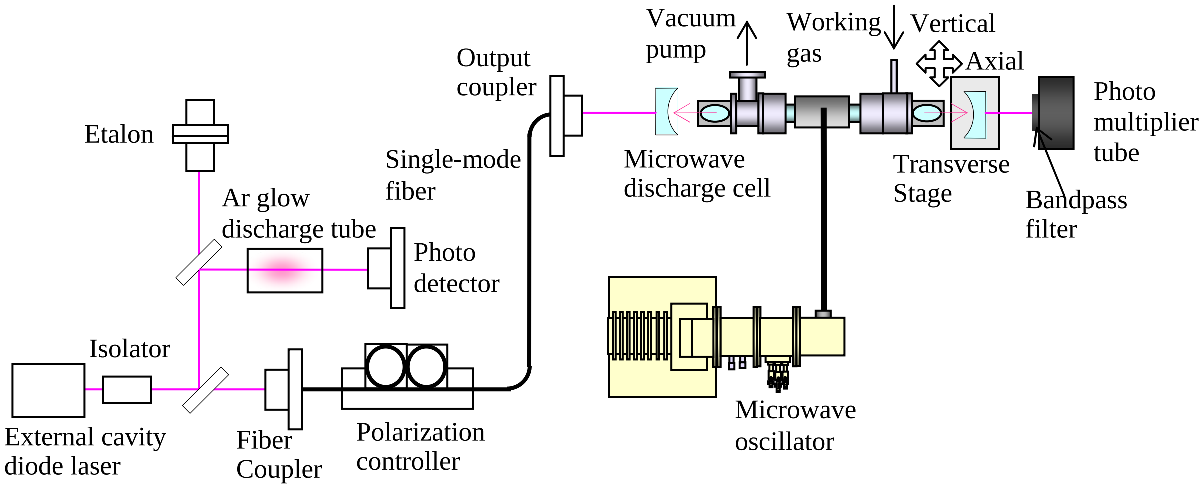


Fig.4 The schematic of measurement system for cavity enhanced absorption spectroscopy

In this research a microwave discharge cell (MC-03II, NIHON KOSHUHA Co., Ltd.) was used as the plasma generator. The microwave discharge cell can generate stable plasma at wide range of low pressure. A schematic the microwave discharge cell and its photo are shown in Fig.2. The size of the quarts tube is 200 mm in length and 8 mm in inside diameter. Its oscillation frequency and input power are 2.4 GHz and 100 W, respectively. The microwave discharge cell was evacuated by a rotary pump and a mechanical booster pump. The vacuum system was connected through a 1/4inch Teflon tube in order to eliminate the mechanical vibration from the vacuum system. A typical CEAS signal through the microwave discharge tube and a single-pass LAS signal through the argon glow discharge tube with an etalon signal are shown in Fig. 3. In this equipment, the absorption signals of atomic argon become small when mass flow rate of oxygen is increased. It is because the electronic temperature in the microwave discharge cell decreases as mass flow rate of oxygen is increased as shown in Fig. 4. When the mass flow rate of oxygen was larger than 20 sccm, the absorption signals of argon atom could not be obtained by single-pass LAS. Using CEAS, the absorption signals of argon atom could be obtained when the mass flow rate of oxygen was less than 60 sccm. In this study, the mass flow rates of argon and oxygen were set as 30 sccm and 10 sccm, respectively. The chamber pressure was maintained about 1.4 kPa in this condition.

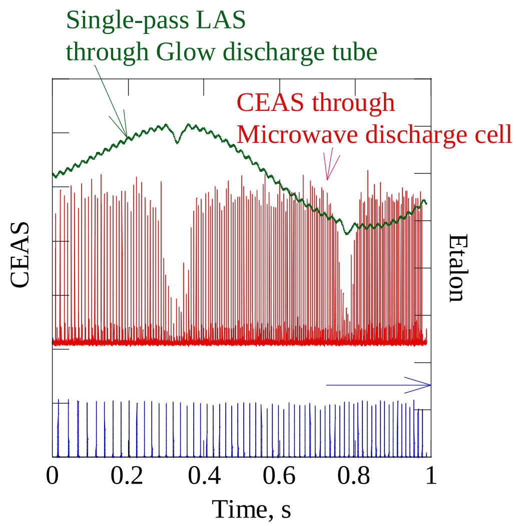


Fig.5 CEAS signal of atomic argon generated by microwave discharge tube, single-pass LAS signal in the glow discharge tube and etalon signal

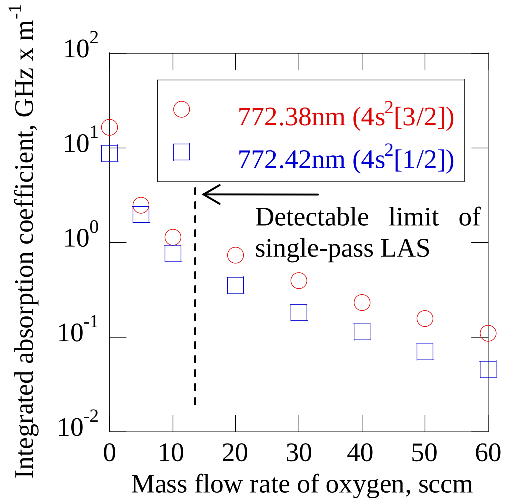


Fig. 6 Integrated absorption coefficient of the microwave discharge cell

IV. Results and Discussion

A. Mechanical vibration of the Vacuum chamber for the Arc heated wind tunnel

The amplitude of the mechanical vibration of the vacuum chamber for the Arc heated wind tunnel was measured by a laser displacement sensor (LK-G500, Keyence Japan) as shown in Fig. 5. The maximum amplitude was about 30μm as shown in Fig. 6. The frequency of this mechanical vibration was estimated as 25 Hz by FFT analysis. The amplitude and the frequency of the translation stage for simulating the mechanical vibration were set as the same values.

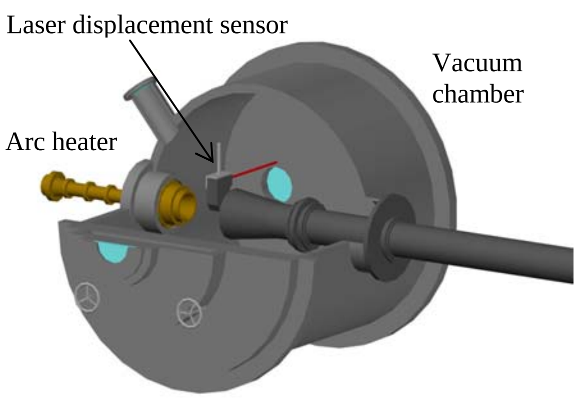


Fig.5 Experimental setup for the measurement of the mechanical vibration of the vacuum chamber for Arc heated wind tunnel

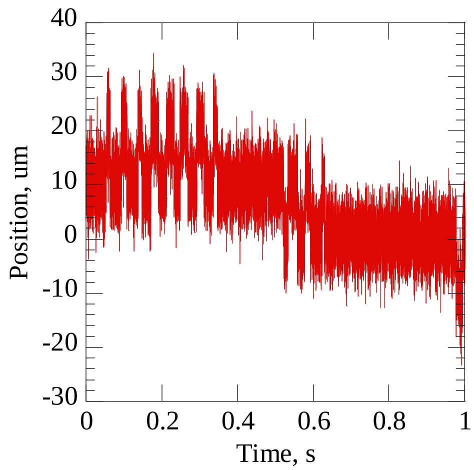


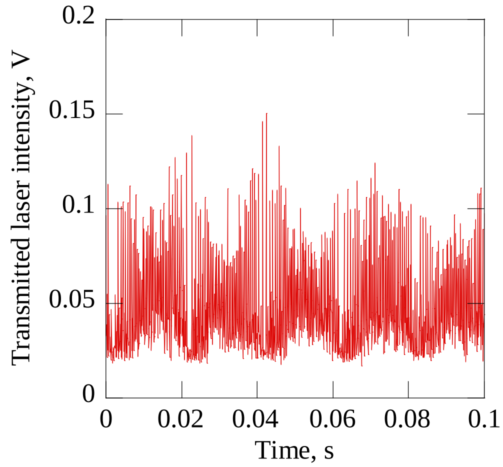
Fig.6 The mechanical vibration of the vacuum chamber for Arc heated wind tunnel

B. Influence of Mechanical vibration on Cavity Enhanced Absorption Spectroscopy

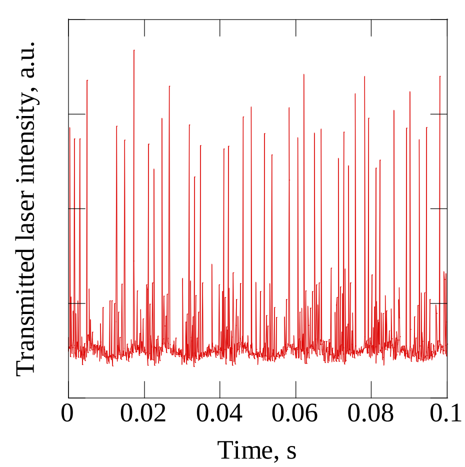
In order to investigate the influence of mechanical vibration on CEAS, one of the high reflectance mirrors which constructed the cavity were vibrated axially or vertically to the laser axis by the translational stage. The amplitude and the frequency of the translation stage for simulating the mechanical vibration were set as 30mm and 25Hz, respectively. The transmitted laser intensities through the cavity are shown in Fig.7. In these cases, the modulation frequency of the laser frequency was about 50GHz/s. In order to compare the each others, the transmitted laser intensity without vibration is also shown in Fig.7-(e). In these frequency regions, there were no absorptions through the plasma. Without the mechanical vibration, high order modes were suppressed and TEM_{00} mode was dominant. With the axial vibration, the laser beam was resonated at many frequencies. With the vertical vibration, the resonated frequencies were also increased because high order modes were increased. Then the resonated laser intensities were more stable with the vertical vibration than those with the horizontal vibration. The transmitted laser frequency fluctuation with the axial or vertical vibration of the forehand mirror was similar with that with the same direction vibration of the backward mirror.

C. Rapid sweep on Cavity Enhanced Absorption Spectroscopy

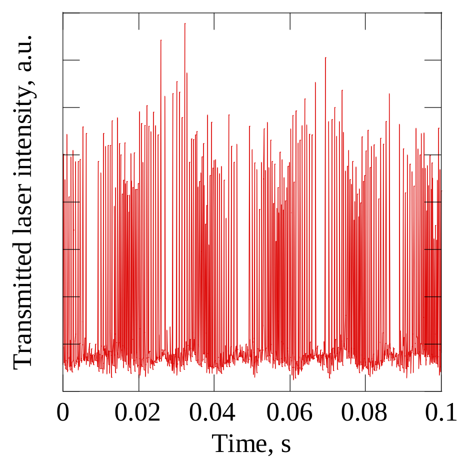
If the laser frequency can be swept faster than the mechanical vibration, the transmitted laser intensity could be stable. Therefore, in order to improve the fluctuation of the transmitted laser intensity, rapid sweep on CEAS was tried. The transmitted laser intensities with rapid sweep with the horizontal or vertical vibration of the backward mirror are shown in Fig. 8. The absorption profiles at 772.42nm of argon with rapid sweep are shown in Fig. 9. In these cases, the modulation frequencies of the laser frequency were about 500GHz/s or 5,000GHz/s, respectively. As the sweep frequency increased, high order modes were suppressed and TEM_{00} mode was dominant. While when the laser frequency was sweep rapidly, the transmitted laser intensity became smaller and the emission ratio from the plasma became larger. As a result, absorbance was underestimated with 5,000GHz/s.



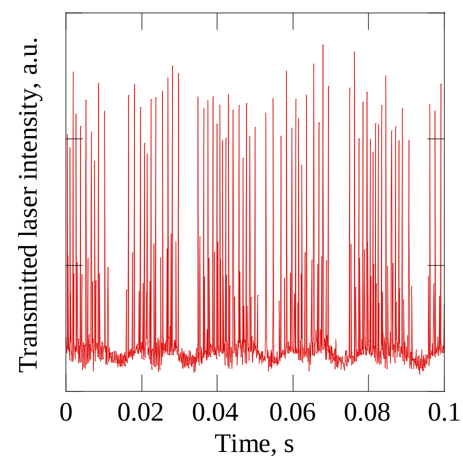
(a) Axial vibration of the forehand mirror



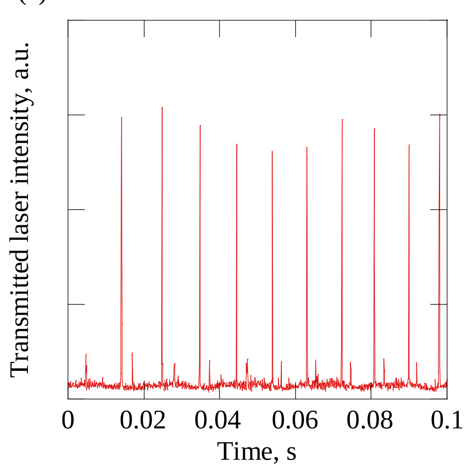
(b) Vertical vibration of the forehand mirror



(c) Axial vibration of the backward mirror

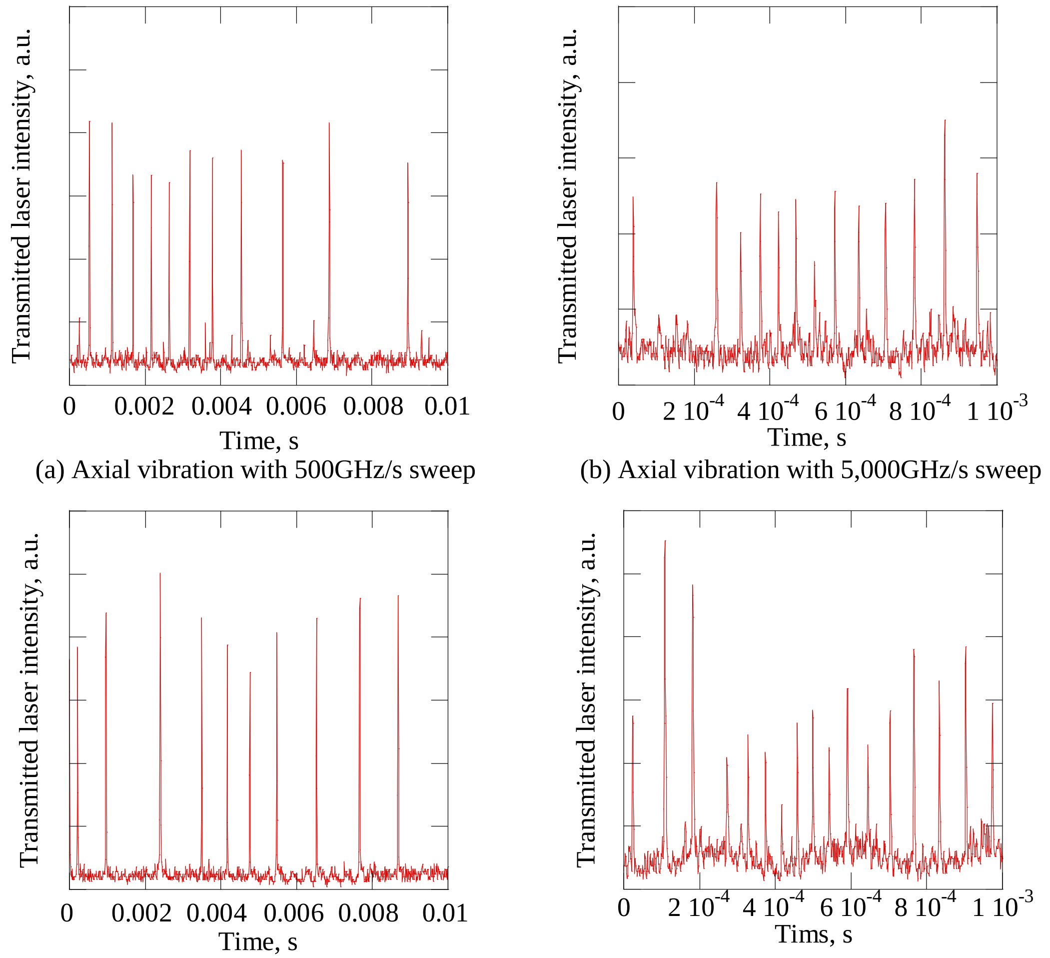


(d) Vertical vibration of the backward mirror



(e) Without vibration

Fig.7 Transmitted laser intensity through the cavity with mechanical vibration. One of the high reflectance mirrors were vibrated axially or vertically to the laser axis. In order to compare the each others, the transmitted laser intensity without vibration is also shown in (e).



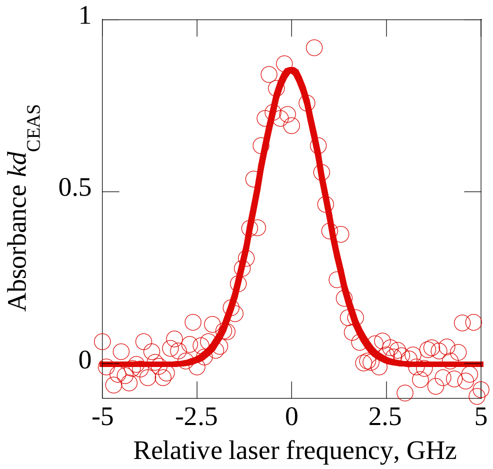
(a) Axial vibration with 500GHz/s sweep

(b) Axial vibration with 5,000GHz/s sweep

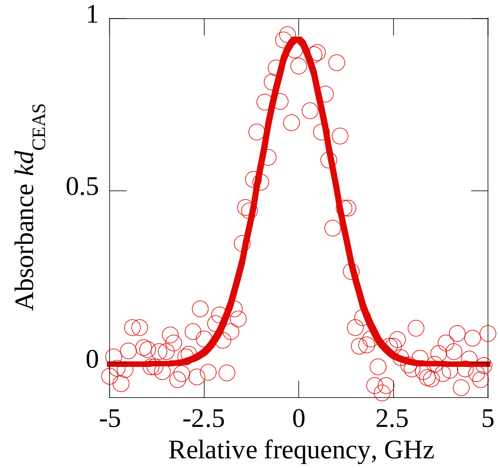
(c) Vertical vibration with 500GHz/s sweep

(d) Vertical vibration with 5,000GHz/s sweep

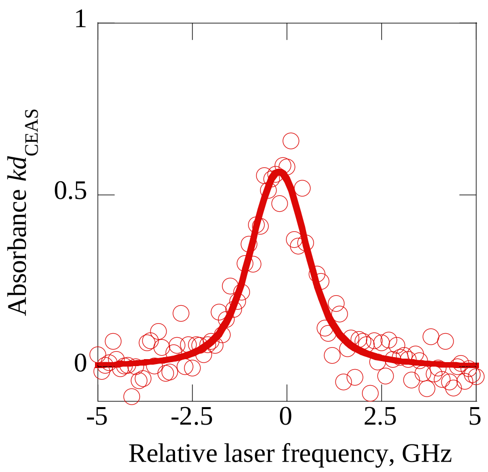
Fig.8 Transmitted laser intensity through the cavity with mechanical vibration of backward mirror axially or vertically to the laser axis with rapid sweep of the laser frequency.



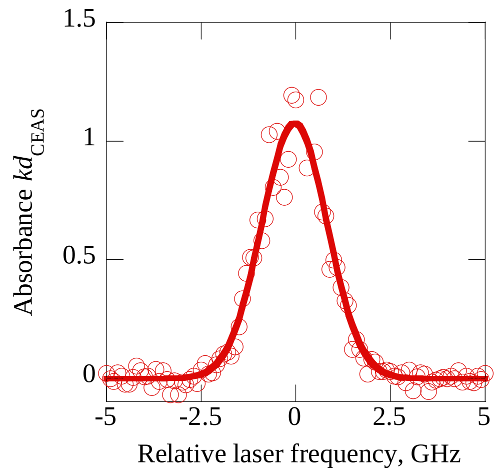
(a) Axial vibration with 50GHz/s sweep



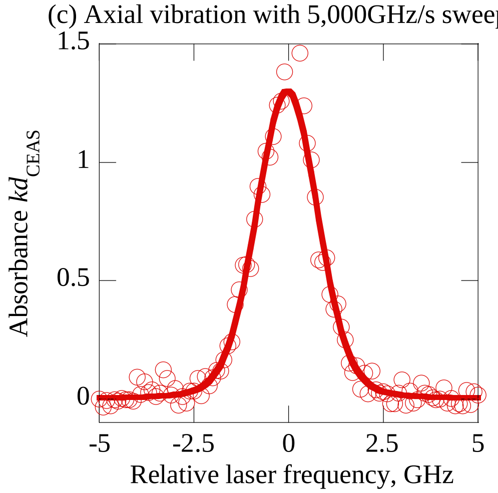
(b) Axial vibration with 500GHz/s sweep



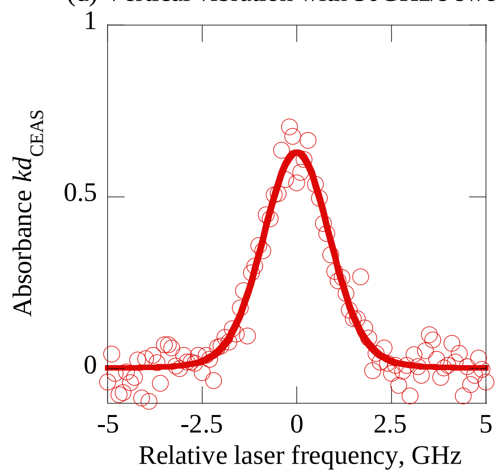
(c) Axial vibration with 5,000GHz/s sweep



(d) Vertical vibration with 50GHz/s sweep



(e) Vertical vibration with 500GHz/s sweep



(f) Vertical vibration with 5,000GHz/s sweep

Fig.9 Absorbance with mechanical vibration of backward mirror axially or vertically to the laser axis with rapid sweep of the laser frequency.

V. Conclusion

In this study, the influence of mechanical vibration on Cavity Enhanced Absorption Spectroscopy was investigated by adding the intentional vibration to the mirror of the cavity and following conclusions are obtained.

1. The amplitude of the mechanical vibration of the vacuum chamber for the Arc heated wind tunnel was measured by a laser displacement sensor. The maximum amplitude and the frequency were about 30μm and 25Hz, respectively.
2. In order to investigate the influence of mechanical vibration on CEAS, one of the high reflectance mirrors which constructed the cavity were vibrated axially or vertically to the laser axis by the translational stage. With the axial vibration, the laser beam was resonated at many frequencies. With the vertical vibration, the resonated frequencies were also increased because high order modes were increased. Then the resonated laser intensities were more stable with the vertical vibration than those with the horizontal vibration. The transmitted laser frequency fluctuation with the axial or vertical vibration of the forehand mirror was similar with that with the same direction vibration of the backward mirror.
3. In order to improve the fluctuation of the transmitted laser intensity, rapid sweep on CEAS was tried. As the sweep frequency increased, high order modes were suppressed and TEM_{00} mode was dominant. While when the laser frequency was sweep rapidly, the transmitted laser intensity became smaller and the emission ratio from the plasma became larger. As a result, absorbance was underestimated with 5,000GHz/s.

Acknowledgements

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References

[1] Auweter-Kurtz, M., Kurtz, H. L., and Laure, S., "Plasma Generators for Reentry Simulation," *Journal of Propulsion and Power*, Vol.12, 1996, pp.1053-1061

[2] Amorim, J. Baravian, G., and Jolly, J., "Laser-Induced Resonance Fluorescence as a diagnostic technique in non-thermal equilibrium plasmas," *Journal of Physics D: Applied Physics*, 2000, Vol.33, R51

[3] Takayanagi, H., Mizuno, M., Fujii, K., Suzuki, T., and Fujita, K., "Arc Heated Wind Tunnel Flow Diagnostics using Laser-Induced Fluorescence of Atomic Species," *AIAA Paper*, 2009, AIAA-2009-1449

[4] Takayanagi, H., Mizuno, M., Fujii, K., Suzuki, T., and Fujita, K., "Arc Heated Wind Tunnel Flow Characterization Measured by Laser-Induced Fluorescence of Atomic Species," *AIAA Paper*, 2009, AIAA-2009-4241

[5] Matsui, M., Takayanagi, H., Oda, Y., Komurasaki, K., and Arakawa, Y., "Performance of arcjet-type atomic-oxygen generator by laser absorption spectroscopy and CFD," *Vacuum*, Vol. 73, 2004, pp. 341-346

[6] Matsui, M., Komurasaki, K., Arakawa, Y., Knapp, A., Herdrich, G., and Auweter-Kurtz, M., "Enthalpy Measurement of Inductively Heated Air Flow," *Journal of Spacecraft and Rocket*, Vol. 45, No. 1, 2008, pp. 155-157

[7] Takayanagi, H., Matsui, M., Komurasaki, K., and Arakawa, Y., "Sensitivity Enhancement in Laser Absorption Spectroscopy for the Diagnostics of High Enthalpy Flows," *AIAA Paper* 2005-0831, Jan, 2005

[8] Kim, S., Jeffries, J. B., and Hanson, R. K., "Measurement of Gas Temperature in the Arc-Heater of a Large Scale Arcjet Facility Using Tunable Diode Laser Absorption," *AIAA Paper* 2005-0900, Jan, 2005.

[9] Takayanagi, H., Matsui, M., Komurasaki, K., Ochimizu, H., and Arakawa Y., "Arc Wind-Tunnel Flow Diagnostics by Cavity-Enhanced Absorption Spectroscopy," AIAA Journal, Vol. 47, No. 5, May, 2009

[10] Griem, H. R., *Principles of Plasma Spectroscopy*, Cambridge Univ. Press, Cambridge, England, U.K., 2005