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Flow Disturbances at super-orbital velocity Using Spectral Analysis in expansion tube HEK-X

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Abstract

Disturbances in the test free stream of the free piston-driven expansion tube (HEK-X) were measured at JAXA's Kakuda Space Center as part of the facility calibration. These measurements were made at very high orbital velocities ranging from 8.5 km/s to 11 km/s. A focused laser differential interferometer (FLDI) with high-frequency response characteristics was used to enable measurements with extremely short test times of a few hundred microseconds. The Hayabusa sample return capsule model (20% scaled model) was used as the test model, and density disturbances inside the shock layer near the stagnation point were measured with FLDI and pressure disturbances were measured with a piezoelectric pressure transducer at the model stagnation point, and the frequency characteristics of FLDI and stagnation point pressure were investigated from their time histories. Because the test duration was short (a few hundred microseconds), a spectral analysis method called SWT (Synchrosqueezed Wavelet Transforms) was employed to investigate the time-frequency analysis. This technique allowed both frequency and time to be analyzed with high resolution. A cross-spectrum analysis of the two measurements was also performed. The analysis confirmed that some characteristic frequency mode disturbances appeared after the arrival of the backward expansion wave.

Keywords: *Expansion tube, super-orbital, time-frequency analysis*

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) has completed sample return projects from asteroids in 2010 and 2020 [1] and [2]. They also work on the following sample return capsule projects [3]. When the sample return capsule returns to Earth from deep space, it re-enters the atmosphere at a super-orbital velocity of more than 12 km/s. Therefore, the shock layer in front of the capsule becomes an ultra-high-temperature flow field where dissociation and ionization occur. JAXA operates a free-piston-driven HEK-X [4-6] expansion tube for aerodynamic studies of the fundamental flow in super-orbits. The expansion tube facility [7] is currently believed to be capable of producing free-stream conditions that most closely simulate the flow during super-orbital re-entry. However, the accuracy of the test results cannot yet be fully guaranteed for use as a design tool. This is due to a lack of understanding of the characteristics of the high-speed shock tube and the test free stream at the final super orbital velocity. Factors include the growth of boundary layers in the tube due to chemical reactions caused by high-speed shock waves in excess of 10 km/s, the expansion process of the equipment nozzle, and disturbances generated by the diaphragm. In addition, the test time is extremely short (several hundred microseconds), and within this short test time, pressure varies from a few Pa to several MPa and temperature from room temperature to over 10,000 K. The extremely high dynamic range requirement makes it difficult to ensure measurement accuracy & precision and is a major obstacle to mechanism elucidation.

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Understanding the characteristics of the disturbances in the test flow, which have been discussed in the past for expansion tubes [8] and [9], is crucial to understanding the shock wave tube mechanism. Furthermore, these disturbances have a significant impact on the accuracy of the test as measurement noise. In particular, although HEK-X can routinely perform 10 km/s tests, the disturbance characteristics of such high-speed test flows have not previously been evaluated at this facility. Therefore, as part of the characterization of the HEK-X test flow, disturbance measurements of the test flow were performed. A blunt head model (Hayabusa sample return capsule 20% scaled model) was used to measure the stagnation pressure disturbance history (pitot pressure) of the model using a piezoelectric pressure transducer. Direct measurement of the density disturbance history inside the model stagnation point shock layer was also attempted using the FLDI measurement technique, which is beginning to be used in wind tunnel testing. The SWT (Synchrosqueezed Wavelet Transforms) time-frequency analysis was performed on the measured pitot pressure and FLDI to ensure both temporal and frequency resolution simultaneously and to extract the characteristics of the frequency modes. In order to derive airflow disturbance correlations, characteristic frequency mode cross-spectrum from the analysis of pressure and density disturbance time series data were described, and conclusions about test flow characteristics were attempted to be drawn from these features. Details of the HEK-X super orbital expansion tube, test conditions, and measurement methods are also described.

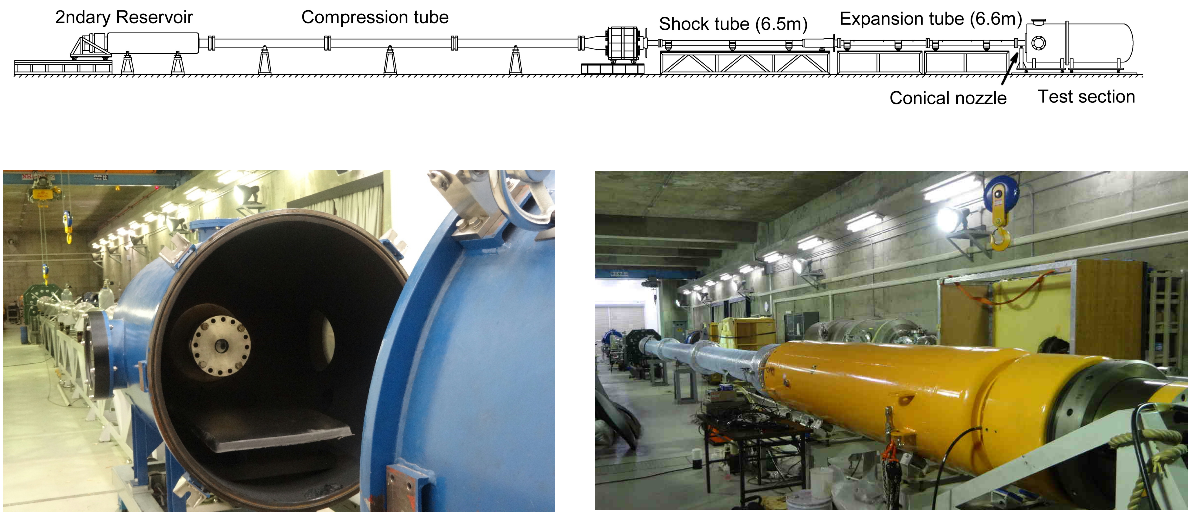


Fig 1. Schematic(top) and photos (bottom) of the free-piston driven expansion tube HEK-X

2. Shock tunnel experiments.

2.1. Expansion tube HEK-X and Hayabusa SRC test model

HEK-X (Figure 1) is a free-piston-driven expansion tube developed to perform basic research on super-orbital flows. The multimodal aerodynamic test facility HEK was conceived initially as a free-piston shock tunnel. HEK-X is one operational mode of the HEK facility. Unsteady expansion occurs in a 6.6-meter expansion tube connected to the end of the shock tube. This process accelerates the shock wave to a higher Mach number, producing higher stagnant pressure and enthalpy. The free-piston shock wind tunnel HEK is designed and operated with the overdrive operation concept [10][11][12], which guarantees high stagnation point conditions despite the relatively small shock tunnel facility. This overdrive operation is the normal mode of operation for the HEK-X and is one of the most notable features of the HEK-X. In this test campaign, a conical equipment nozzle was attached to the end of the expansion wave tube. The total length of the equipment nozzle is 700 mm, the outlet diameter is 190 mm, and the expansion angle is 4.8 degrees. A final shock wave velocity of Vs = 8.5 and 10 km/s were selected as the test condition. Table 1 shows the operating conditions for this test campaign. Both operating conditions for the free-piston driver were the same, and the final shock wave velocity, Vs = 6 to 10 km/s, was changed by adjusting the shock tube and expansion tube's initial pressure. The expansion tube wall pressure history was measured with a piezoelectric pressure gauge (PCB Piezotronics PCB113B24) mounted on the expansion tube wall.

Table 1. Operation conditions of the present test campaign

Shock speed condition	Vs=8.5 km/s	Vs=10 km/s
Secondary reservoir pressure (MPa)	5.57	5.57
Compression tube initial pressure (kPa)	94.2	94.2
Piston mass (kg)	21.4	21.4
Diaphragm rupture pressure (MPa)	52	52
Shock tube initial pressure (kPa)	50	10
Expansion tube initial pressure (Pa)	50	10

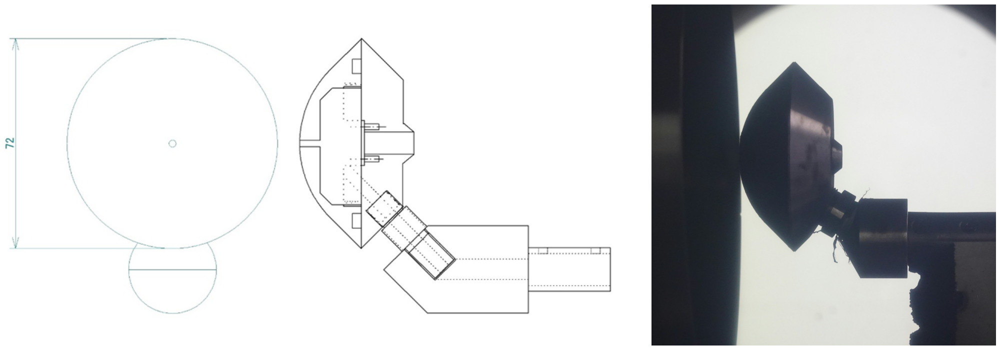


Fig 2. Left: Schematic of the Hayabusa SRC 20% scaled model. Right: The test model is installed in the HEK-X test section.

A 20% scaled Hayabusa sample return capsule model was used as a test model. The model is made of 18-8 stainless steel, and the radius of curvature of the stagnation point is 50 mm. A piezo electric pressure transducer (PCB Piezotronics PCB113B24) with the orifice of 1.5 mm diameter was installed at the stagnation point of the model. A Chromel-Constantan miniature coaxial thermocouple was also used to measure stagnation point heat flux, but this is not mentioned in this report. Figure 2 shows a schematic of the model and a photograph of the model installed in the HEK-X test section.

2.2. Focused Laser Interferometry

Recently, a measurement technique called focused laser differential interferometry (FLDI) has been widely adopted to analyze disturbances in hypersonic flow fields [13][14]. The measurement upper limit is an order of magnitude higher than that of piezoelectric pressure transducers, which are as high as MHz. In addition, in contrast to piezoelectric pressure sensors, which are susceptible to mechanical vibrations of the model, this method is not affected in any way. These two advantages make it suitable for use in shock tunnels, a measurement environment where test times are relatively short (a few hundred microseconds), and the effects of model vibration due to high dynamic pressure during airflow startup are often problematic for piezoelectric pressure transducers. In this measurement, the laser beam was focused on the bow shock wave impact layer approximately 0.5 mm upstream from the model stagnation point. In addition, a He-Ne laser with a wavelength of 628 nm was used as the light source, and an optical measurement system was set up with a focal distance of 0.28 mm between the two FLDI beams. Fig.3 shows the FLDI setup for the HEK-X expansion tube test section.

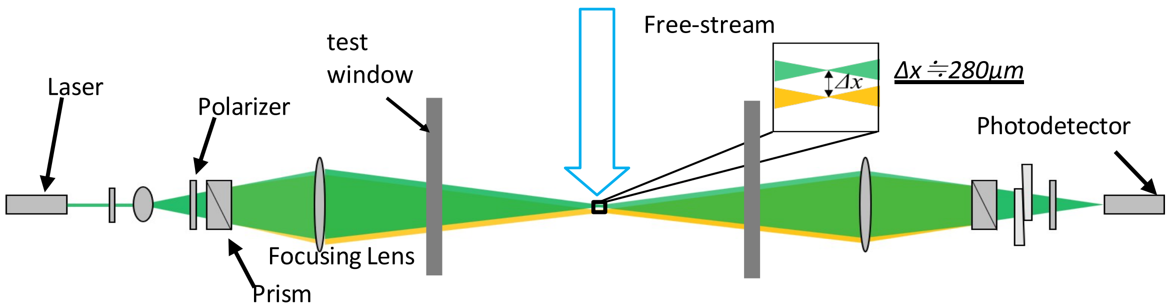
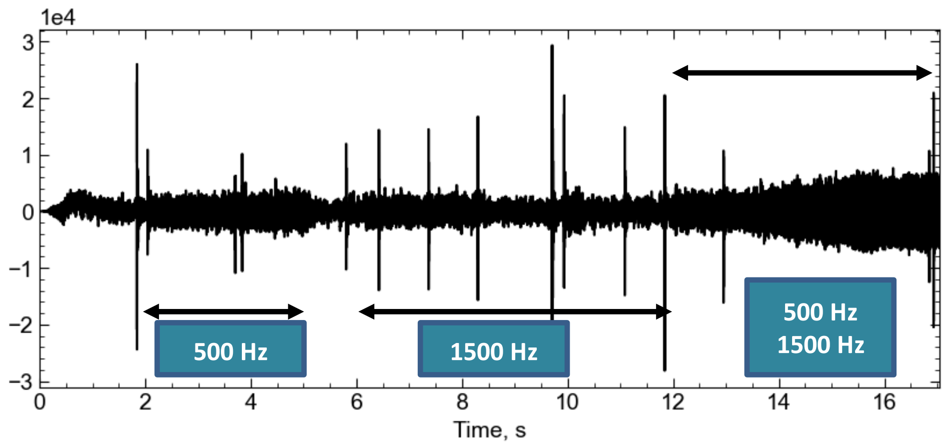


Fig 3. The FLDI setup for HEK-X.

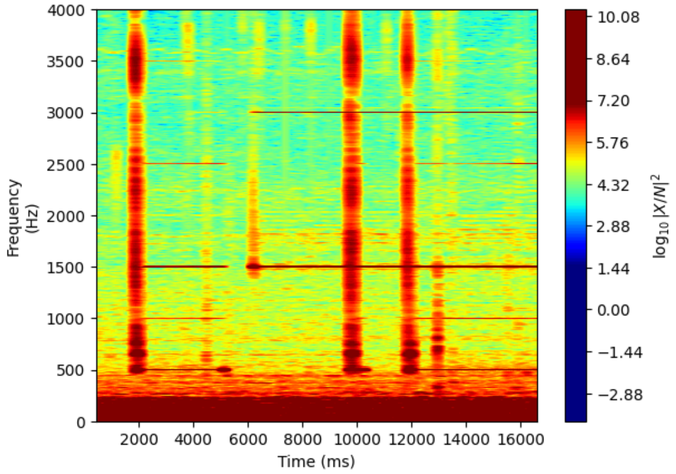
3. Time-frequency analysis

As already mentioned, the expansion tube test is extremely short, with a test time of only a few hundred microseconds, and the measurement results cannot be treated as stationary. To analyze non-stationary phenomena, time-frequency analysis is commonly used. Short-time Fourier transform (STFT) is a typical method of time-frequency analysis; STFT uses a window function to divide the signal into segments of fixed duration and applies Fourier transform to obtain the time variation of frequency. Since the basis of the STFT is the Fourier transform, the trade-off between time resolution and frequency resolution makes it difficult in principle to ensure the resolution of both. Alternatively, the continuous wavelet transform (CWT) [15] is another method for time-frequency analysis; the CWT analyzes signals by shifting a function called the mother wavelet in time. Unlike STFT, in which the frequency resolution is fixed once the width of the window function is determined, CWT is considered suitable for analyzing non-stationary signals because the frequency resolution varies with frequency. Furthermore, the recently proposed SWT (Synchrosqueezed Wavelet Transforms) [16][17], although called a heuristic and ad hoc method, has the potential to improve frequency resolution by rearranging STFT and CWT results along the frequency axis. In this study, we tested this method for time-frequency analysis of HEK-X ultrashort-time measurements.

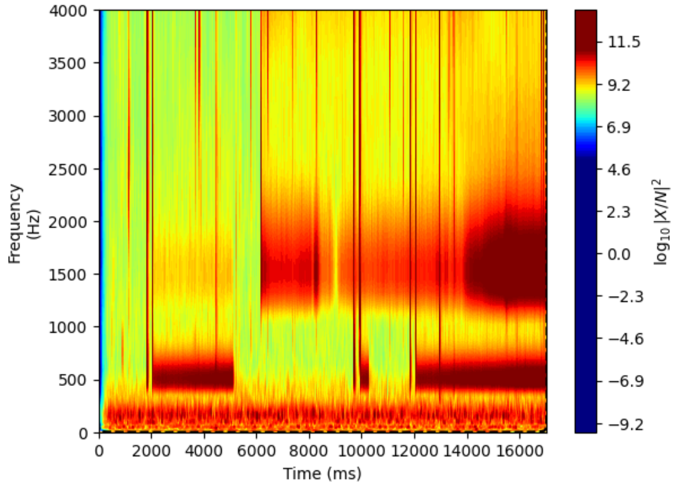
First, the analysis method was validated: time-series data of two signals at 500 Hz and 1500 Hz were given as benchmarks and compared to STFT and CWT to see if the SWT analysis method has sufficient frequency and time response capability. Figure 4(a) shows the input time series data: a 500 Hz sine wave was given from 2 to 5 seconds, a 1500 Hz sine wave from 6 to 12 seconds, and a superimposed 500 Hz and 1500 Hz sine wave from 12 to 15 seconds. Figures 4(b), 4(c), and 4(d) show the results of STFT, CWT, and SWT analysis of the input time series data, respectively; it is observed that STFT and CWT lack resolution in frequency and time responses, while SWT achieves finer resolution than the other two methods.



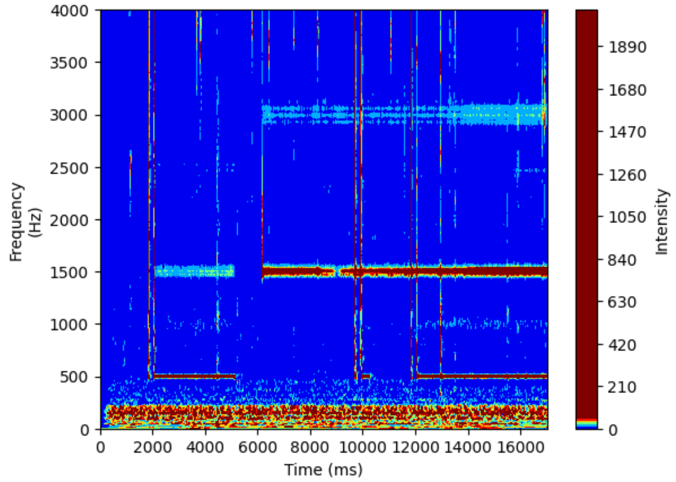
(a)



(b)



(c)



(d)

Fig 4. (a) Input time series data: a 500 Hz sine wave was given from 2 to 5 seconds, a 1500 Hz sine wave from 6 to 12 seconds, and a superimposed 500 Hz and 1500 Hz sine wave from 12 to 15 seconds. (b) Short-time Fourier transform (STFT) result (c) Continuous wavelet transform (CWT) result and (d) SWT (Synchrosqueezed Wavelet Transforms) result.

4. Results and Discussion

The left and right panels of Figure 5 show the FLDI signal history and model stagnation point pressure (mainstream Pitot pressure) history obtained under 8.5 km/s and 10 km/s shock speed conditions, respectively. The spectrograms of these measured signals obtained by SWT are shown in Figures 6 (8.5

km/s) and 7 (10 km/s). The FLDI signal for each condition is shown on the left and the free-stream stagnation point pressure history is shown on the right. FLDI history and stagnation point pressure history spectrograms both show some high-frequency modes at several hundred kHz, but after the contact surface is reached (after t=0.4 ms at 8.5 km/s and after t=0. 25 ms at 10 km/s), no characteristic disturbances were observed during the test period. Therefore, a cross-spectrum analysis was performed for FLDI and stagnation point pressure. Cross-spectrogram results for shock wave velocities of 8.5 km/s and 10 km/s are shown in the upper and lower panels of Figure 8, respectively; for the 8.5 km/s condition, multiple frequency modes appeared after about 330 μs, suggesting that different disturbances occurred in the airflow around 330μs. Similarly, for the 10 km/s condition, multiple modes appear after 130 μs.

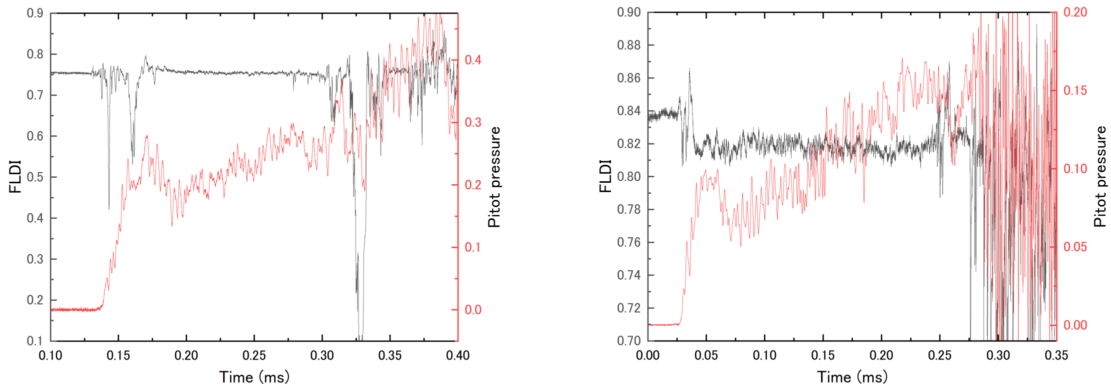


Fig 5. FLDI history on the left and stagnation point pressure (Pitot pressure) history on the right.

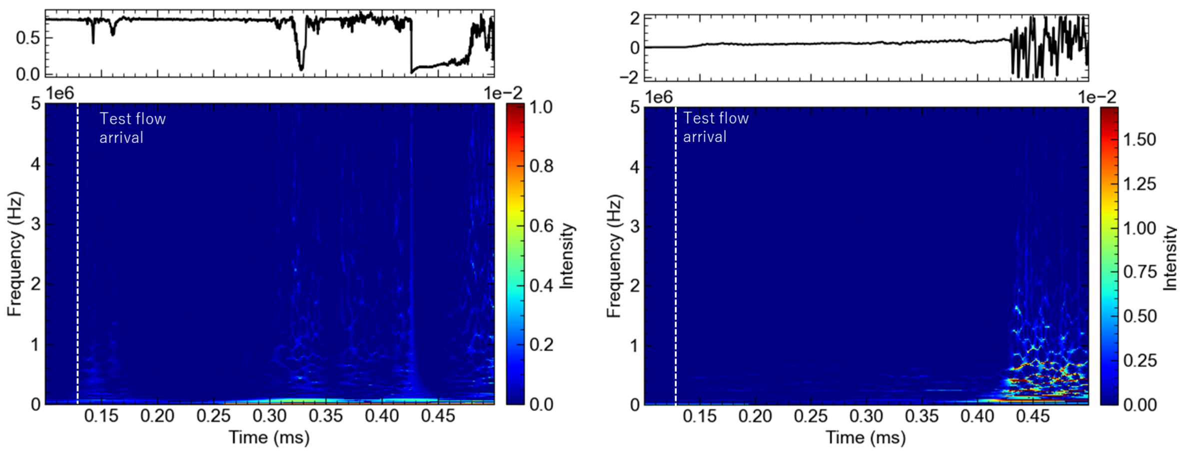


Fig 6. The SWT spectrogram obtained under 8.5 km/s shock speed condition. FLDI measurement history on the left and stagnation point pressure (Pitot pressure) history on the right.

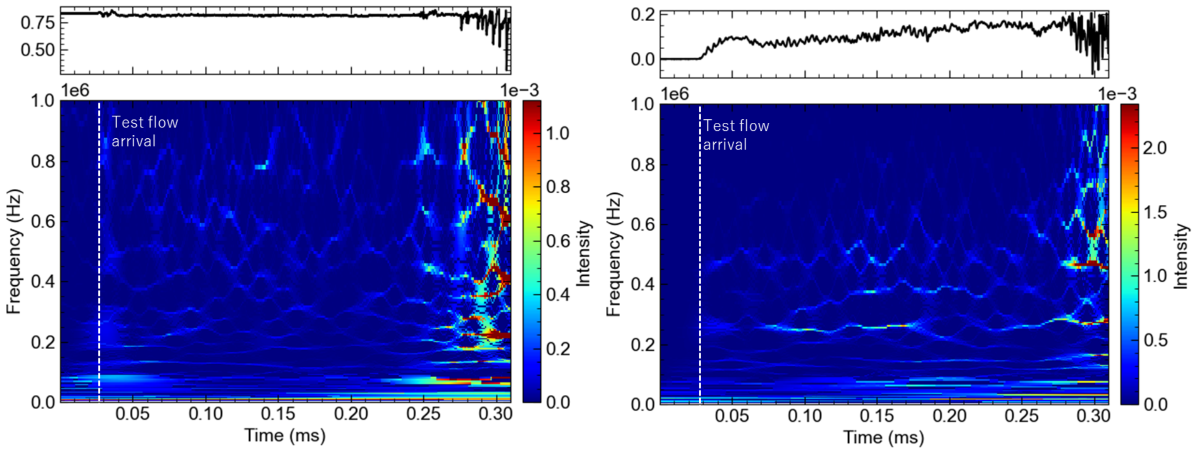


Fig 7. The SWT spectrogram obtained under 10.0 km/s shock speed condition. FLDI measurement history on the left and stagnation point pressure (Pitot pressure) history on the right.

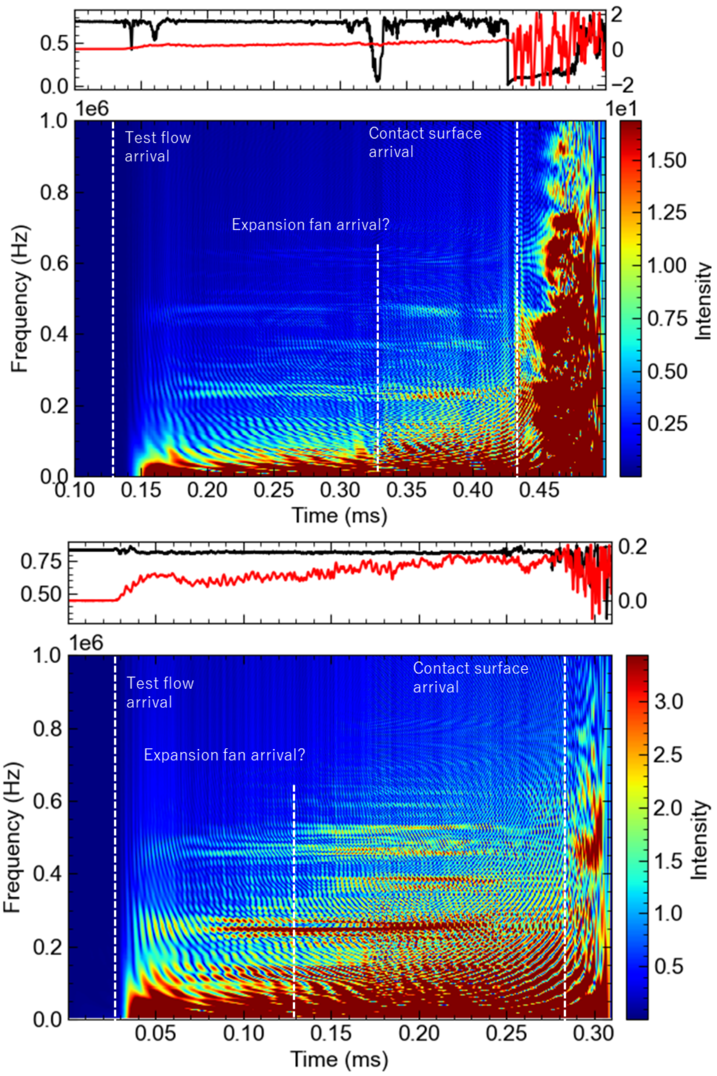


Fig 8. Cross-spectrograms of FLDI measurement history and stagnation point pressure (Pitot pressure) history obtained under shock speed of 8.5 km/s condition (top) and shock speed 10km/s (bottom).

The timing of the increase in disturbance modes is similar to that observed in previous HEK-X spectral results. Figure 9 shows the emission spectra of the same Hayabusa model stagnation points obtained in previous emission spectroscopy experiments at HEK [18]. The emission of H and N atoms, which require high enthalpies, was quenched within 100 μs of the arrival of the test flow under Vs=10 km/s conditions. Under the Vs=8.5 km/s condition, the emission was quenched in a little over 200 μs after the arrival of the test flow. The shock wave velocity conditions of 8.5 km/s and 10 km/s are assumed to be caused by a decrease in the enthalpy of the airflow because the wavefront of the receding expansion wave reflected by the contact surface reaches the model less than 200 μs after the arrival of the airflow and less than 100 μs after the arrival of the airflow, respectively. The extinction time measured in the emission spectroscopy experiment is almost the same as the timing of the increase of the disturbance mode in the present cross-spectrum analysis; although it cannot be discussed in detail because only the test results at 8.5 km/s and 10 km/s have yet been analyzed, it is possible that this frequency mode may serve as a marker to quantify the testable time of the expansion tube However, it is suggested that this frequency mode may serve as a marker for quantifying the testable time of the expansion tube.

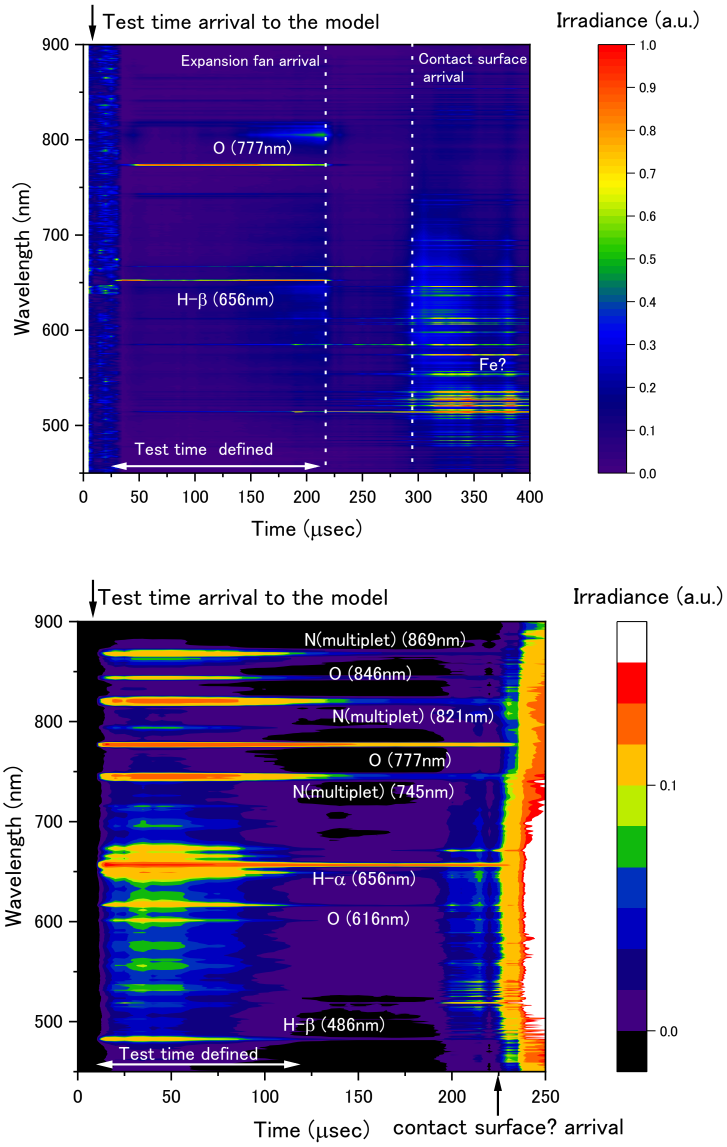


Fig 9. A spectrum image of the emission spectroscopy (top: Vs=8.5km/s, bottom: Vs=10km/s) was obtained [18].

5. Summary

As part of the calibration of the super orbital ground shock wind tunnel facility, disturbances in the test freestream of the free piston driven expansion tube (HEK-X) were measured. These measurements were made at very high orbital velocities, ranging from 8.5 km/s to 11 km/s. A focused laser differential interferometer (FLDI) with high-frequency response characteristics was used. The Hayabusa sample return capsule model (20% scale model) was used as the test model. Density disturbances inside the shock layer near the stagnation point were measured by FLDI and pressure disturbances (pitot pressure) at the model stagnation point were measured by a piezoelectric pressure transducer, and the frequency characteristics of frequency FLDI and stagnation point pressure were investigated from their time histories. A time-frequency analysis method called SWT (Synchrosqueezed Wavelet Transforms) was used to examine the frequency characteristics for short test times (several hundred microseconds) and to evaluate the cross-spectrum between the FLDI signal history and the pressure history. This method allowed us to analyze both frequency and time with high resolution. The analysis confirmed that the number of disturbance modes increased after the arrival of the reflected backward expansion wave, which signified the end of the test period. This result suggests that the measurement of the disturbance modes can be used to identify the test time of the expansion tube.

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