論文の内容の要旨

論文題目　「Characteristics of Acoustic Waves Generated by Flow Instability of Supersonic Jets」
和訳:「超音速ジェットの変動が生み出す音響場特性に関する研究」

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When a rocket launches, it exhausts a plume (rocket plume) which is of the supersonic jet condition. A rocket plume emits very strong acoustic waves, especially low frequency ones, which may critically damage the pay-loads of the rocket such as artificial satellites because they are very light and fragile. Thus accurate prediction and reduction of the sound pressure level (SPL) of acoustic waves, especially low frequency ones, are important. In order to predict acoustic waves from the rocket plumes, a semi-empirical method based on experimental and launch data was proposed. However, it is known that there is a difference between an actual SPL and a predicted one. In addition, though these semi-empirical methods are based on many past data, mechanisms such as noise-emission, noise-directivity and noise-source have not been well-discussed due to the difficulties of handling the experimental or launch data.

Thus a new prediction method based on a more accurate model for the jet acoustic waves is needed. In order to build a new engineering model based on physics, it is necessary to obtain detailed information of the flow fields and acoustics fields. Therefore, the analyses on the acoustic waves, mainly Mach waves, which is dominant acoustics from the rocket plume, from a simple single supersonic free jets are needed for improving the prediction method. In this study, especially following three engineering issues are investigated. First, the verification of this non-dimensionalization for high Mach number supersonic jets is conducted. The effective non-dimensionalization for the prediction of the acoustic waves enables us to reduce the parameters. However, this normalization for the high Mach number supersonic jet is not verified. Second, the Mach number and the temperature effects are investigated. The past studies did not include fluid parameters strongly such as the Mach number and the temperature. However these parameters seem to have very strong effects on the acoustic characteristics. Third, the source characteristics of Mach waves are investigated, taking an advantage of a computational approach. The past studies were not able to clarify the source characteristics of Mach waves because of difficulty of experiment.

With regard to the numerical methods, in this study, the monotonically integrated large eddy simulation approach is conducted with the seventh order WCNS, the tenth order compact scheme and the third order TVD-RK schemes under the 10 million computational grid system.

For the prediction of acoustic waves from the rocket plume, the verification of the effective normalization which bases the ideally expanded Mach number and the design Mach number is conducted. In this study, this normalization is verified for three supersonic jets whose ideally expanded Mach number are 3.0 where the designed Mach number is set to be 3.0, 3.5 and 4.0. The SPL distribution and the spectrum of several points of these three cases show good agreements within the error of 2-3dB, especially two cases, design Mach number 3.0 and 3.5, shows an excellent agreement, while there are some differences probably due to the shock associated noises in the upstream side. Present results show that the fact reported by Tam for the relatively low Mach number supersonic jet is applicable to the higher Mach number supersonic jet. For the prediction of acoustic waves from the rocket plume, namely one of the purposes of this research, this result implies that rocket parameters can be reduced.

Then, the other parameters, (ideally expanded) Mach number effects and temperature effects are investigated. A Mach number effect on flow fields is found to be potential core becomes longer with increasing Mach number. Mach number effects on acoustics fields are as follows. As Mach number increases, 1) SPL becomes higher, 2) the near field directivity of the jet becomes wider, 3) the direction of maximum acoustic emissions becomes larger and 4) the peak Strouhal number slightly becomes lower. On the other hand, a temperature effect on flow-fields is found to be that potential core becomes shorter with increasing temperature. Temperature effects on acoustics fields are as follows. As temperature increases, 1) SPL becomes slightly higher, 2) the width of directivity do not seem to change so much in spite of the change of potential core-length, 3) the direction of maximum acoustic emission becomes larger and 4) the peak Strouhal number becomes lower.
Temperature effects on potential core length noted above, namely it becomes shorter with increasing temperature, is very strong. Resulting potential core length of hot jets corresponds to that guessed by the study in the past. In order to predict flow-fields of rocket plume, this point seems to be very important. In addition, with increasing Mach number and temperature, SPL becomes higher, while peak Strouhal number becomes lower. Specifically Mach number rather affects SPL than the peak Strouhal number whereas temperature rather affects the peak Strouhal number than SPL.

With regard to the analysis of source characteristics, focused array methods, correlation of velocity fluctuations and normalization of source spectrum are conducted.
First, the focused array method which is one of microphone array methods is applied to the computational flow-fields and the resulting source position of Mach waves are discussed.

In the result, Mach wave source region is inside of the environmental supersonic region which is defined the local velocity and the ambient sonic speed.
In addition, the lower frequency source is located at the downstream side and spreading compared with the higher frequency ones. Second, the supersonically convective velocities of the disturbances assumed as the Mach wave sources are computed. These convective velocities of disturbances are visualized with the vector whose direction denotes expected as the angle of Mach wave radiation and the absolute value denotes the strength of correlations. These vectors exist at the almost similar region which is calculated as the source region with the focused array methods. In addition, the direction of the vector seems to be the almost same as that of the strong acoustic wave emission observed in the overall or octave band SPL distributions. Third, normalization of the source frequency is discussed. This idea originates the study in the past. The original model shows the good collapse, but has no physical background. To construct a more reliable model, the simple physical model is proposed. As a result, the normalization seems to work well except for the temperature effect on the shear layer fluctuation. Finally, using the above normalization, it is shown that the lowest frequency of Mach waves probably is decreasing with increasing the ratio of environmental supersonic region to the potential core length.

These knowledge and data obtained in this study are very useful ones for improving the prediction model of acoustic from a rocket plume.