1D Numerical Study of Nonlinear Propagation of Finite Amplitude Waves in Traveling Wave Tubes with Varying Cross Section

Zhineng Zhang and Ling Zheng
The State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400044, China.

Tingfei Yan and Yao Wu
Beijing Institute of Spacecraft Environment Engineering, Beijing 100029, China.

(Received 30 November 2018; accepted 2 August 2019)

The nonlinear acoustic problem of a finite amplitude plane wave propagating along the axial direction in a traveling wave tube is studied. Based on the one-dimensional Westervelt equation, a one-dimensional nonlinear wave equation is derived in which the cross section of the traveling wave tube is considered. The two-order finite difference scheme is used to solve the nonlinear wave equation. The nonlinear propagation characteristics of a finite amplitude wave in the traveling wave tube is analyzed. In the expanding transition section, the acoustic pressure amplitude of the acoustic wave decreases with the increase of the cross-sectional area of the pipeline. The nonlinear characteristics of the acoustic wave show waveform distortion and harmonic growth. The waveform distortion becomes more serious in the rear of traveling wave tube than in the front of the tube. Considering the acoustic reflection condition at the mouth, the influence of differently shaped diffusion sections on the acoustic pressure distribution in the test section is investigated. The larger the change rate of the diffusion section in an area, the less amplitude of the sound pressure, and the nonlinear effect of the sound wave propagation is weakened. These nonlinear wave propagation characteristics in a travelling wave tube provide important guidance for both designing and the method of fundamental solutions.

These results showed that the sound pressure at the outlet of the horn was affected by the piston’s vibration speed, frequency and horn shape. The results also showed that the exponential horn and hyperbolic horn had higher sound source radiation efficiency.

1. INTRODUCTION
The vibration and noise caused by takeoff, inter-stage separation and two ignitions will cause damage to the satellite and its components during the launching process. Therefore, environmental simulation experiments must be carried out underground before launch. A high-intensity acoustic traveling wave tube can be used to both simulate the acoustic environment of the aerospace structure during flight and to check the anti-acoustic fatigue capability of the structure under a strong sound field, which has become an important test method for ground tests. The analysis of the nonlinear propagation law of the finite amplitude wave in the high strength acoustic traveling wave tube can provide a scientific basis for the optimization design of the traveling wave tube structure and the formulation of the noise test method, which is of great significance to the development of the aerospace industry.

Due to the complexity of the nonlinear propagation of the finite amplitude waves in the pipeline, especially for both the complex traveling wave tube structure and its boundary conditions, it is difficult to obtain accurate solutions by the analytical method. Acoustic numerical computation is an effective way to solve the nonlinear propagation problem of finite amplitude waves. At present, there are a large number of documents based on the finite element method, the boundary element method, and the method of fundamental solutions. These methods are used to calculate the nonlinear sound field in two-dimensional and three-dimensional pipeline models. However, the precise model will greatly increase the calculation time. In order to reveal the acoustic propagation law of a simple symmetrical pipe structure, the three-dimensional model can be simplified to a one-dimensional problem. Based on the Kuznetsov wave equation, T. Tsuchiya used the finite element method to analyse the nonlinear propagation characteristics of finite amplitude waves in one-dimensional straight tubes and two-dimensional exponential tubes, and analyse its frequency-domain response characteristics by Fourier transform as well. Hallaj used the finite difference time domain method to solve the Westervelt equation and to analyse the problem of nonlinear propagation of finite amplitude waves in an ideal medium. The equation comprehensively considers the nonlinear terms and the dissipative items and can freely select the calculation dimension according to the requirements of the working conditions. The equation is intuitive and simple for performing mathematical modeling. However, the equation cannot consider the influence of pipe section change on the nonlinear acoustic propagation in one dimension. Hou Wei et al. used high-order low-dispersion numerical schemes to solve the one-dimensional finite-amplitude acoustic propagation for a finite exponential horn and analyzed the waveform distortion and the effects of horn’s geometry. The results showed that the sound pressure at the outlet of the horn was affected by the piston’s vibration speed, frequency and horn shape. The results also showed that the exponential horn and hyperbolic horn had higher sound source radiation efficiency.