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Numerical investigation of switching mechanism for the supersonic jet element

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ABSTRACT

Based on the unsteady viscous flow simulation, the flow characteristics inside the supersonic jet element have been investigated numerically. The corresponding initial switching process has been overall divided into two major stages. The results have shown that the switching process for the supersonic jet flow is an extremely complex process, which can include the complex shock system evolution, the free shear layers together with the boundary layers evolution and multiple vortex region unsteady evolution etc. The presence of the switching oblique shock near the control port is not the necessary condition to make the jet deflect, but its formation is good for the early transverse extension of the stripping vortex zone. A new concept named minimum control mass flow rate has also been proposed and emphasized. The Viscosity and adverse pressure gradient have been found to be the key factors for the occurrence of flow separation to shorten the switching time. The vortex structures at different switching time together with the variations (thrust, static pressure as well as oblique shock waves etc.) inside the supersonic jet element have been obtained computationally and analyzed in details.

1. Introduction

The supersonic jet element (SJE) is the execution unit in the attitude control system for different spacecrafts. Its performance (such as the control force, switching time, energy efficiency and reliability etc.) can play an extremely important role in controlling the accuracy of the whole space flight [1–3]. The SJE is also called fluidic amplifier. On one hand, it could be used as the logic control system components to achieve a variety of logic functions. On the other hand, through a small energy control signals, it also could be served as an implementation part of the control system and offer much large energy or torque directly [4–7]. Nowadays the supersonic jet element is applied to the Multiple Launch Rocket System project as the implemental components of the control system. Raja [8] had numerically investigated the mixed convection flow and heat transfer characteristics in a two-dimensional plane, laminar offset jet issuing parallel to an isothermal flat plate. The results had shown that the reattachment length is strongly dependent on both the Reynolds number and the Grashof number for the range considered. Sawyer [9] had applied the analysis to the flow due to a jet emerging at an angle to a flat plate and given a good prediction of the length and average pressure of the recirculation region for a particular value of an entrainment-ratio parameter.

Silnikov and Chernyshov [10] had applied the mathematical model of “differential conditions of dynamic compatibility” to theoretically analyze the evolution of the incident shock in the plane overexpanded jet flow or in the axisymmetric one. The corresponding analytical results can be applied to avoid jet flow instability and self-oscillation effects at rocket launch, to improve launch safety and to suppress shock-wave induced noise harmful to environment and personnel. Sary [11] had modeled the plasma synthetic jet actuator's operation. Parametric studies on the geometrical aspects of the actuator as well as its electrical inputs have also been performed, improving its operation and efficiency and resulting in a quasi-periodic pulsed regime. Svensson [12] had used three different turbulence models to predict mean velocity field as well as turbulence characteristics in the near zone of a 6×6 in-line array of unconfined confluent round jets. The numerical results had been compared with experimental data acquired by Particle Image Velocimetry. The results had shown that the jet's position within the configuration has a substantial impact on the velocity decay, length of the potential core, and the lateral displacement of the confluent jets.

However, the switching mechanism of the supersonic jet components still lacks of a deep understanding. The corresponding switching reasons are always simply attributed to the oblique shock and the

Abbreviations: F, total thrust (N); e, dissipation rate (m^2/s^3); k, Kinetic energy (m^2/s^2); f_l, left outlet thrust (N); m, mass flow rate (K); f_r, right outlet thrust (N); Ma, Mach number; l_{out}, pressure outlet (Pa); Ps, main gas source pressure (bar); Δt, time step (s); T, temperature (K); P_{O1}, point from main jet inlet (−0.0062,0.042); t, switching time (s); P_{O2}, point from main jet inlet (0.0062,0.042)

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Coanda effect. Based on this, our present research will further analyze the flow characteristics of the switching process and then reveal the specific switching mechanism for the jet supersonic components.

The paper is organized as follows. Section 2 describes the governing equations including a brief description of the adopted numerical algorithm. The validation method and results will be also presented and discussed. Section 3 will specifically discuss the flow field before switching, thrust as well as static pressure distribution during switching, switching mode, formation and evolution of oblique shock, jet leaving the attached wall layer etc. The changes for different parameters in the whole switching process are also investigated in details. The paper will end with brief concluding remarks.

2. Simulation setup and accuracy test

2.1. Simulation setup

As shown in Fig. 1(a), the supersonic jet element (SJE) is a kind of amplifying Element without moving parts which always uses the gas as the working medium. Fig. 1(b) shows the work mechanism of the SJE. Compared with the other flexible parts of the amplifier (such as pneumatic or hydraulic slide valve, rotary valve or diaphragm valve), the supersonic jet element has many advantages, such as the low accuracy manufacture and low cost, which also has no moving parts, so the work process does not appear "stuck" in. As implemental components of the control system, the SJE's work performance (control, switching time, energy efficiency, working reliability et al.) has an important role in the control accuracy of the system. Fig. 1(c) shows the surface girds of the SJE. In modeling the whole SJE, the quality and size of the mesh generation will directly affect the accuracy of the computational results. So during meshing the structural grids of the SJE, we will adopt the method of size function to control the grid size (It doesn't change the entire structure of the network topology). And the parts of structural grid can be refined for the whole Element, and the structural grid can be smoothed and swapped, enhancing the accuracy of the simulation.

The Gauss-Seidel method is used to calculate the inner fluid field of the supersonic jet element. The governing equations of flow are Reynolds Averaging Navier-Stokes equation. The model of turbulence is Realizable k-epsilon model, and Two-layer zonal model is used near the wall.

2.2. The accuracy test

The thrust in the attached wall condition is an important measurement to indicate the performance of supersonic jet components good or bad. Therefore, we will first calculate the pressure thrust created by a variety of primary gas source pressure, and then under the same conditions, the thrust value corresponding to the main gas source pressure will be obtained eventually. The verification of the thrust force in the switching process are verified by a single channel air conditioning system [13]. The test system consists of four parts: high pressure and large flow pressure regulating system, data acquisition and processing system, jet element test bench and control table.

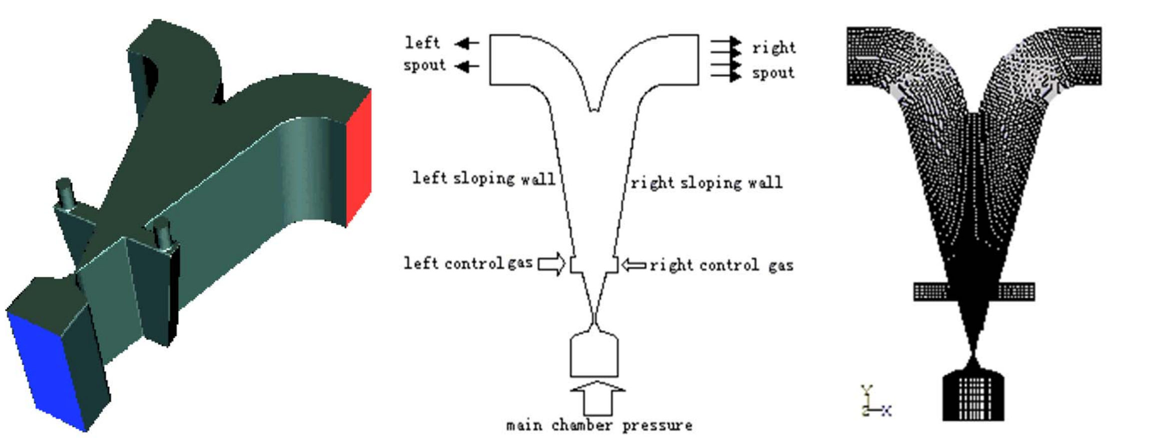
As shown in Fig. 2, the high pressure and large flow pressure regulating system consists of high pressure compressor (WZ2.3/450) and high pressure gas cylinder group (TGP-50 L/35 MPa), which will be used to provide the high gas resource and control supersonic airflow.

Dynamic test rack is used to fix the fluidic element, and the jet component test bed movable frame is installed with two high frequency and accuracy force sensors. The sensors will be used to monitor the changes of the total thrust during the switching process. The data acquisition and processing system is used to collect the voltage signal from the force sensor and then to process the corresponding noise. The cut-off valve, control valve conversion, data acquisition and processing will be totally controlled by the control table.

Table 1 has showed the thrust corresponding to the main gas source pressure (Ps) and test stands for the total thrust in the X direction of the jet components. f_l and f_r stand for their own thrusts of two outlets, $\overrightarrow{F} = \overrightarrow{f_l} + \overrightarrow{f_r}$, Error stands for the relative error between the calculation (F) and test. The maximum and minimum difference can be calculated within 12% and 0.3%, respectively. Considering the accuracy of the measurement method and the simulation errors, the comparisons are showing reasonable overall quantitative agreement, showing the accuracy of the current simulation method.

2.3. Grid sensitivity test

The accumulation of numerical error and dependence of simulation results on grid size should be studied for the particular problem. For each particular problem accumulation of errors could be different. Besides, for one and the same simulation it is different for different stages of simulations being the function of the number of time steps. Therefore, estimating precision and errors accumulation are extremely necessary for large simulations of the complex fluid problem. And accumulation of error is proportional to the square rote of the number of time steps. It should be evaluated for each numerical simulation, especially for the unsteady flow state, which has been investigated by Smirnov [14,15] in details. The corresponding research had revealed that the relative error of integration in 1D case can be simplified as: $S_1 \approx (1/N_1)^{k+1}$ in the uniform grid, where N_1 is the number of cells in the direction of integration and k is the order of accuracy of numerical scheme. Then it can be summed up as:



(a) 3D Structure shape (b) Work mechanism (c) Computational grids(slice)

Fig. 1. The work mechanism and grids for the supersonic jet element.