Simulation Study on Flow-induced Vibration Characteristics of Multi-nozzle Ejector

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Abstract. The ejector is an important power source for intermittent wind tunnel. In order to accurately predict the flow-induced vibration (FIV) response, numerical simulation based on fluid-structure coupling method was carried out. Firstly, three-dimensional unsteady constant simulation on the flow field of ejector was done, using the renormalized k-ε model. The ejector inlet and outlet mass flow were basically consistent with design, and the relative error of Mach number in the third-stage nozzle was 1.79%. Secondly, in the one-way coupling simulation, the MPCCI software was performed. Thirdly, the calculated vibration spectrum was obtained. The simulation results could be found in good agreement with experiment, and the domain frequency relative error was 4.27%.

1. Introduction
The ejector is a device that transport fluid by the entrainment principle of high-speed flow, act like pump [1]. Due to the rapid response and simple structure, it’s widely used in industrial field. Such as achieving rapid pressure depressurization in ejector wind tunnels, transporting media in natural gas and mining industries, and increasing thrust at low speeds in pulse detonation engines.

The internal flow of ejector is extremely complicated, which was determined by the work mechanism. For gas ejector, due to the influence of internal flow shock, vortex, airflow mixing pulsation and resonance [2], serious vibration problems may threaten the operation safety of equipment. Especially in large-injection wind tunnels and laser weapon pressure recovery systems, severe structural vibration could affect equipment performance and even cause fatigue damage [3].

With the rapid development of chemical laser weapons and pulse detonation rocket engine technology, research on ejector performance has become a hot topic in academia. A series of research results [4-6] have been published, on parameter optimization and internal flow numerical simulation of ejector. During the development of wind tunnel design and laser pressure recovery system, China Aerodynamics Research and Development Center found that the vibration of multi-nozzle ejector might show different manifestations in different applications, and the characteristics are far more complicated than ordinary wind tunnel sections. In a wind tunnel, tear occurred in nozzle support plates as the vibration concentrated. In another wind tunnel the outer shell of the exhaust ejector cracked because of vibration. For pressure recovery system, the vibration of work platform exceeded the standard, which was more difficult to accept.

For the problem of pressure recovery system, Liu Zongzheng [7] designed a damping device with a weight-coupled rubber-metal spring parallel structure, which effectively reduced the vibration amplitude. To achieve vibration reduction, Ma Yue-yin [8] optimized the transition part structure, using finite element calculation and experimental test methods. Wang [9] obtained the ejector mode of
the pulse detonation rocket engine by experimental means and optimized the ejector parameters. Nie Junfeng [10,11] studied the respiratory vibration mechanism and dynamic load identification of the engine ejector, achieved good results.

Although the research in the literature [7~11] had achieved certain effects in engineering, they were just cases analysis based on specific object. All the forward research focused on the entire structural response of ejector, which were excited by multi-vibration sources. To provide technical guidance for ejector vibration reduction and structural optimization, the common problems of ejector vibration should be studied from the perspective of FIV, and the vibration mechanism should be obtained using the numerical simulation method.

2. Vibration Source Analysis
The source of ejector structure FIV could be very complex, and the vibration frequency band was wide. The vibration of ejector was mainly caused by airflow pulsation, eddy current, airflow impact caused by valve the action, resonance. When ejector work, the upstream valve opened quickly, causing severe airflow surges in ejector system tubing. Then the airflow was ejected through the nozzle, and mixed with the secondary airflow in mixing chamber. In this process, a rapid static pressure decrease occurred along the wall of ejector. The ejector principle was shown in Figure 1. On the one hand, the gas velocity in ejector could be several Mach number, the turbulent boundary layer might separate and form eddy. On the other hand, with the velocity and pressure of the mixed flow changed periodically, the pulsating airflow generated and interacted with structure continuously, which would cause system vibration. When the above three frequencies closed to the natural frequency of structure, resonance occurred.

![Figure 1. The schematic diagram of ejector.](image1)

A three-stage multi-nozzle ejector was chosen to be the research object, with a total length of 5 meters nearly. There were 12 nozzles in each stage, divided into two layers of circular uniformity as shown in Figure 2. The design parameters could be found in Table 1.

![Figure 2. Three-stage ejector structural model.](image2)
Table 1. Design parameters of the ejector.

| Stage | Inlet Pressure | Inlet Mass flow | Outlet Mach Number |
|-------|---------------|-----------------|-------------------|
| First | 0.2MPa        | 0.23kg/s        | 3.6               |
| Second| 0.34MPa       | 1.13kg/s        | 3.0               |
| Third | 0.97MPa       | 5.91kg/s        | 2.8               |

3. Internal Flow Field Simulation
The internal flow field of ejector was mainly determined by the supersonic flow emitted from nozzle. The ejector nozzle outlet was the interface of supersonic flow and subsonic flow. In the upstream of the outlet, the continuous gas with high pressure expanded and accelerated quickly, while the downstream was the intense mixing area. So, the outlet was the most complex position of the entire flow field. The nozzle part should not be simplified during model.

Since the structural size of nozzle was one or two orders of magnitude smaller than the overall structure of ejector, the computational cost would be enormous if the same grid was used. The immersion boundary method was used to generate the body mesh and Cartesian grid. The Cartesian grid was encrypted by the Octree method at the nozzle flow path and the small size of the flow feature. The total mesh size was about 1100 Million, the result of the division shown in Figure 3.

![Figure 3. Fluid grid of ejector inner fluid field.](image)

The ejector medium was dry air. In the simulation, the gas was regarded as ideal gas and all structural walls were regarded as adiabatic wall, the remaining boundary conditions were shown in Table 2.

Table 2. The table of boundary conditions.

| Condition | Secondary Point | Inlet 1 | Inlet 2 | Inlet 3 | Outlet |
|-----------|-----------------|--------|--------|--------|--------|
| Total Temperature/K | 300     | 300    | 300    | 300    | 300    |
| Total Pressure/kPa    | 101.5   | 200    | 340    | 970    | 101.5  |

The two-equation renormalization k-\( \varepsilon \)model was used in the simulation, which was applied in fast strain, medium vortex and local transition flow filed usually. The results showed that the mass flow rate of the three-stage ejector gas collection chamber were 0.22 kg/s, 1.07 kg/s, and 5.37 kg/s, respectively, and the inlet flow rate of the venturi nozzle was 0.06 kg/s, which were basically consistent with the design value.

Figure 4 showed the pressure and Mach number distributions in the axial section of the ejector. As can be seen from Figure, the Mach number at the exit of the third stage ejector nozzle was about 2.75, and the relative error with the design was 1.79\%, which could be found to be 2.8 in Table 1.
4. Flow-Induced Vibration Calculation

The fluid-solid coupling algorithm could be divided into one-way coupling and two-way coupling. When fluid pulsation caused solid structure deformation, if solid structure deformation affected the flow field obviously, it could be regarded as two-way coupling, if the effect could be ignored, it was one-way coupling. The ejector FIV was a one-way coupling problem. When Xi Zhidie et al. studied the one-way coupling structure, the fluid-solid coupling dynamic equations of general structure were derived [12]:

\[
\Gamma\ddot{x}(X, t) = f(X, t) \quad (1)
\]
\[
\Gamma = M + \frac{\partial^2}{\partial t^2} + C \frac{\partial}{\partial t} + K + \Gamma \quad (2)
\]
\[
f(X, t) = f_s(X, t) + f_f(t) \quad (3)
\]
\[
f_s(X, t) = -M_s \frac{\partial^2 x(X, t)}{\partial t^2} - C_s \frac{\partial x(X, t)}{\partial t} - K_s x(X, t) \quad (4)
\]
\[
(M + M_s) \frac{\partial^2 x(X, t)}{\partial t^2} + (C + C_s) \frac{\partial x(X, t)}{\partial t} + (K + K_s) x(X, t) = f_f(t) + f_s(X, t) \quad (5)
\]

\(\Gamma\) was the structural operator, its concrete form depended on the shape and motion form of structure. \(f(X, t)\) was the excitation vector, which could be obtained from flow equation. \(f_s(X, t)\) related to the structural motion, named as motion-related fluid force. \(f_f(t)\) was fluid excitation force, which was independent of the structural motion, only determined by fluid motion. \(M_s\), \(C_s\), \(K_s\) was additional mass matrix, additional damping matrix and additional stiffness matrix respectively. The equations
had certain applicability, but for different structures, the calculation of the relevant additional matrix still needs to be specifically modeled and analyzed.

The coupling between the fluid model and the structural model was performed using MPCCI software. The ejector structure response spectrum obtained was shown in Figure 5. As can be seen from the figure, the ejector has significant peak response with peak points of 12.2 Hz and 29.9 Hz, while the amplitude could be found as 0.065 g and 0.018 g respectively.

The test spectrum could also be found in Figure 6, the dominant frequency relative error between simulation and experiment was 4.27%. Among them, 12.2 Hz close to the second-order natural frequency of the structure, 11.91 Hz, and the relative error is 2.43%.

![Figure 5. FLV spectrum of simulation and experiment.](image)

5. Conclusion
(1) In flow field three-dimensional unsteady simulation, the inlet and outlet mass flow, Mach number were basically consistent with the design. The relative error of the third stage ejector was 1.79% compared with design.
(2) The FIV frequency spectrum of ejector was obtained. The domain frequency relative error was 4.27% with experiment.
(3) The domain frequency calculated closed to the second-order structure frequency, the relative error was 2.43%.

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