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The nonlinear multi-physics coupling of airframe-propulsion integration for the air-breathing launch vehicle

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Abstract

The coupling problem of airframe-propulsion integration is serious for air-breathing vehicle. The vibration of the inlet will induce the obvious oscillation of the performance of aerodynamics and propulsion, which brings great challenge to the design of the airframe-propulsion integration and control system. The multi-physics coupling problems are studied for such vehicle's configuration. The analyzed method is established based on CFD, CSD and quasi one dimensional method. For the configuration of airframe-propulsion integration, the fluid-structure-propulsion coupling performance is analyzed, which is used to study the multi-physics coupling problems. It's clear that oscillating characteristics of the integrated performance. The results can be used to guide the design of airframe-propulsion integration and control system.

Keywords: *Nonlinear, multi-physical coupling, airframe-propulsion integration, Air-breathing launch vehicle*

Nomenclature

A(x) - Matrix of cell volumes obtained from a finite volume discretization of the fluid subsystem
F - Viscous force
M - Mass matrix
f^{int} - Structural internal force
f^{ext} - vector of external force applied to the structural system
v_i - Aerodynamic parameters in the combustor
γ_j^i - The coefficient of the equation for the combustion
$\tilde{\mathbf{K}}_c$ - Transfer matrix relating the nodal motions at the fluid/structure interface
$\tilde{\mathbf{K}}$ - A dimensional fictitious stiffness matrix of the mesh motion subsystem
u - Structural deformation
x - The deformation of aerodynamic mesh

1. Introduction

The traditional relationship of vehicle's airframe and engine is different for air-breathing vehicle, which will lead to strong coupling [1] [2]. For wide envelope and large scale air-breathing vehicle, the vehicle's stiffness and vibration frequency are very low due to the large flight dynamic pressure and large scale airframe. The influence of structure vibration on airframe-propulsion integration is not negligible.

There is serious aerothermoelastic problem for air-breathing vehicle. As the in-depth study of the integrated coupling mechanism, the researchers realized that the elastic deformation and the

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aerodynamic heating had a significant impact on the coupling performance of airframe-propulsion integration. Jack J. McNamara[3] studied the aeroelastic and aerothermoelastic behavior in hypersonic flow. Adam J. Culler[4] studied the coupling problems of fluid, aerodynamic heating and structure. For the coupling problems of aeroelasticity and airframe-propulsion integration, Andrew D. Clark[5] established the analyzed model, which computed the response characteristics of the configuration under the influence of aeroelasticity by the combination of CFD and engineering estimation method. The influence of fuselage's deformation on integrated performance was cleared. The method could also be used to the analysis of dynamic characteristics for the integrated vehicle. A set of coupling analysis software ASTE-P was developed by the Patrick Hu[6]~[9] of the Korea advanced dynamics research center, which could be used to study the dynamics of the whole fuselage, and supported the coupling analysis and optimization of multi physics and multi fidelity.

This paper is mainly focused on the problems of airframe-propulsion integration, especially on the multi-field coupling problems. The coupling model is established by multi-fidelity method. The fluid-structure-propulsion coupling problems are studied, and the coupling phenomenon and coupling characteristic is obtained, which can be used to direct the design of hypersonic air-breathing vehicle.

2. The coupling model of multi-physics field

The CFD is applied to the analysis of inlet, and the combustor is analyzed by quasi one dimensional method. Assuming the fluid-structure coupling effect of the inlet on the combustor is one-way, that is, the combustion has no influence on the inlet. The fluid-structure-propulsion model for the airframe-propulsion integration is shown in Fig.1.

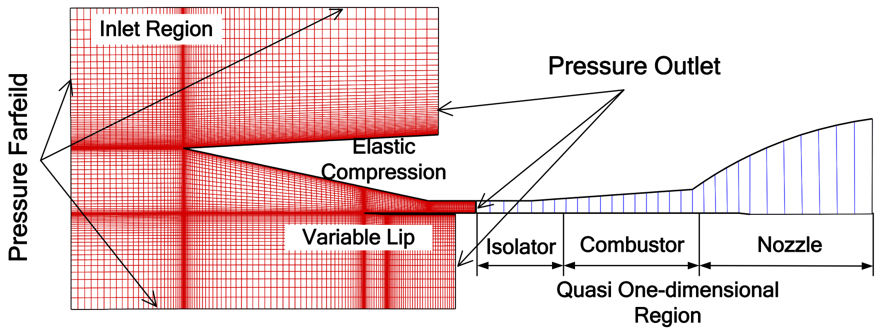


Fig 1. The fluid-structure-propulsion model for the airframe-propulsion integration

3. The method of the multi-physics analysis

Assuming the structure of the engine is rigid, the equation of fluid-structure-propulsion coupling motion can be expressed as

$$\left(\mathbf{A}(x)\mathbf{w}\right)_{,t} + \mathbf{F}\left(\mathbf{w},\mathbf{x},\dot{\mathbf{x}}\right) = 0 \tag{1}$$

$$\mathbf{M}\mathbf{u} + \mathbf{f}^{\mathrm{int}}\left(\mathbf{u},\dot{\mathbf{u}}\right) = \mathbf{f}^{ext}\left(\mathbf{u},\mathbf{w}\right) \tag{2}$$

$$\frac{d\mathbf{v}_j}{d\mathbf{x}'} = \sum_{i\neq j}\gamma_j^i \frac{d\mathbf{v}_i}{d\mathbf{x}'} \tag{3}$$

$$\tilde{\mathbf{K}}\mathbf{x} = \tilde{\mathbf{K}}_{\mathbf{c}}\mathbf{u} \tag{4}$$

$$v_{j,0} = \frac{1}{\sum_i \rho_i \dot{x}_i}\sum_i \rho_i \dot{x}_i w_i \tag{5}$$

Eq. (1) is N-S equation with conservation form based on finite volume discretization. The Eq. (2) is a structural dynamic equation including the internal force and the external force, where the internal force is the internal stress produced by the structural deformation, and the external force is aerodynamic force. Eq. (3) is the quasi one dimensional flow control equation of the engine. In the process of fluid-structure-propulsion coupling analysis, the aerodynamic performance analysis requires boundary conditions provided by structure. The relationship is shown in Eq. (4). The performance analysis of the engine requires the inlet's boundary conditions of the aerodynamics, and its relationship is shown in Eq. (5).

Under the assumption that the structure of the engine is rigid, the fluid-structure-propulsion coupling problems are the problems of the fluid-structure interaction (FSI) and fluid-propulsion interaction (FPI). The FSI is the vibration of inlet's compression and lips. The FPI is the interaction of inlet and engine. In each time step, the once data exchange of FSI and FPI is completed. The analysis of structure and propulsion is based on the aerodynamic results, but the aerodynamic analysis is also based on the results of structure and propulsion. The mesh deforms in each iteration step. The coupling of propulsion and structure can be neglected, but they influence each other by fluid.

The analyzed process of fluid-structure-propulsion coupling is shown in Fig.2.

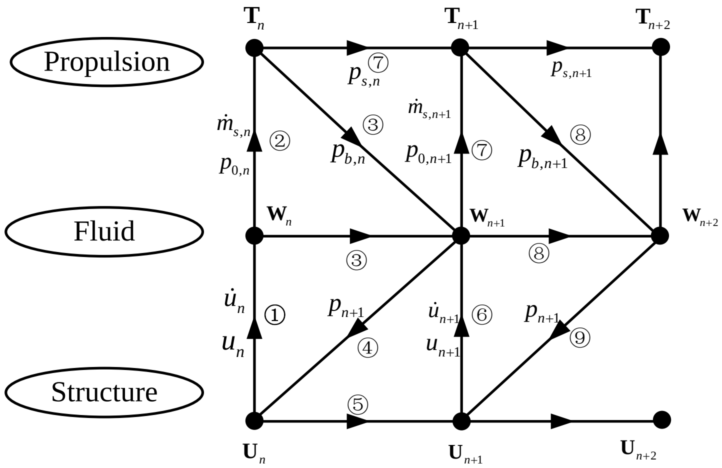
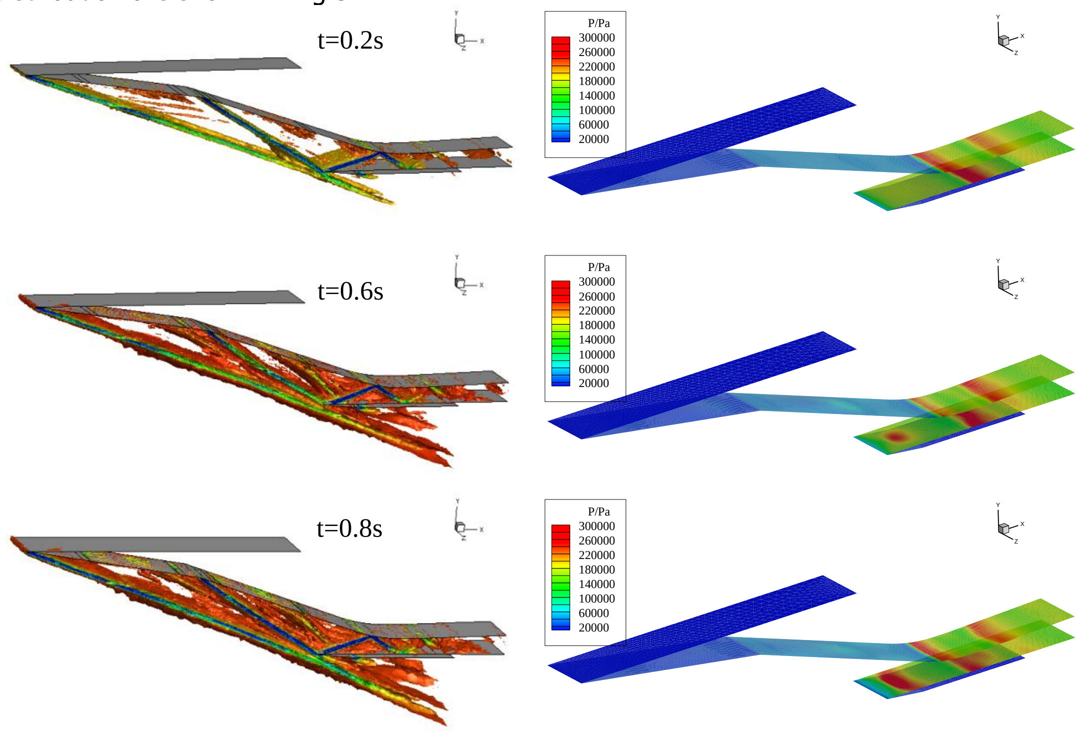


Fig 2. The analyzed process of fluid-structure-propulsion coupling

4. Results and discussion

Under the FSI of the compression surface of the inlet, the vortex distribution and wall pressure distribution are shown in Fig.3.



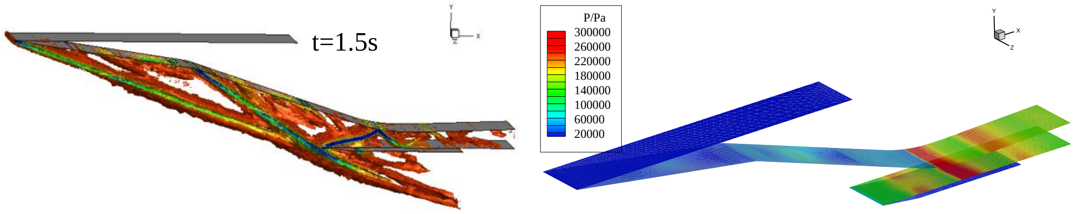


Fig 3. The flow field of the inlet at different time

The FSI will lead to the oscillation of the performance of the inlet. Based on the flow performance on the outlet of the inlet, the performance of the propulsion is obtained by quasi one dimensional method. Assuming the equivalent ratio of the ramjet is 0.8. The fluid-structure-propulsion coupling performance is characterized by the nest thrust of the engine, which is integrated by the pressure. The final results are shown as Fig.4.

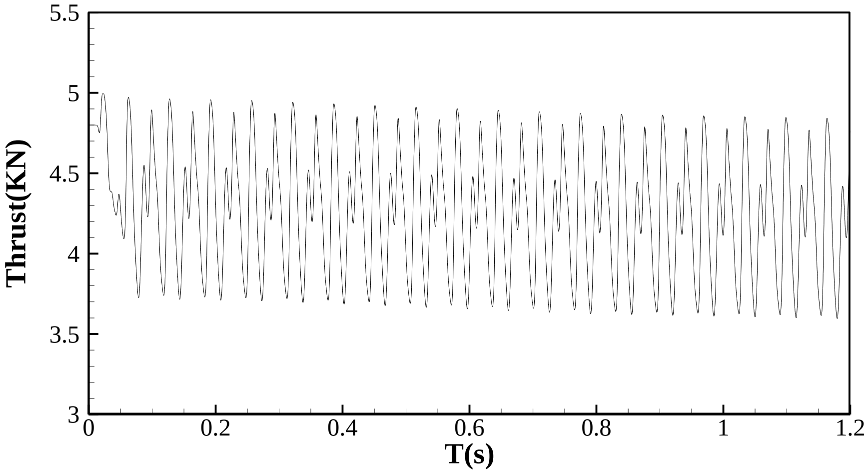


Fig 4. The coupling performance of the airframe-propulsion integration

Under the influence of the elastic oscillation on the first and two stage compression surface of the inlet, the oscillation amplitude of the nest thrust is about 1.25mm. Therefore, the FSI has a very obvious influence on the performance of the propulsion. Under the influence of the FSI, the net thrust has a continuous downward trend. So the time effect on the engine's performance cannot be ignored.

Under the influence of the FSI on the compression surface of the inlet, the oscillation of the net thrust shows quasi periodic phenomenon. If the FSI of other parts of the vehicle such as fuselage and inlet's lip is considered, the fluid-structure-propulsion coupling will be more complex, which will be studied in the following.

5. Conclusion

The fluid-structure-propulsion coupling problems are studied, and the coupling motion equation is established. Based on the coupling method, the multi-physics coupling performance is obtained. The results show that the vibration of the inlet will induce the oscillation of the integrated performance. The average performance tends to reduction as the time goes on, which needs to be studied intensively.

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