Numerical Studies of Acoustic and Thermal Coupling in Sonic Fatigue Tests for Hypersonic Vehicle

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Numerical simulations of sound-fluid coupling at high temperature were conducted in this work to assist sonic fatigue experiments, where a high intensity sound input is imposed on the test specimen heated at 1200°C. Our analysis shows that the noise induced by the unsteady horn flow and thermal fields is negligible compared to the high intensity horn noise. Then sound propagation in a fluid-thermal coupled background flow is computed by using linearized Euler equations and geometrical shielding effect is calculated simultaneously. 2D and 3D simulations of reverberation room cases are conducted at different frequencies from 100Hz to 1kHz, which provides insights for engineering designs.

I. Introduction

In aeronautic and astronautic testing experiment, reverberation room (Fig. 1) is effective and convenient apparatus for sonic fatigue tests. Harsh environment like high temperature, high intensity sound or vibration should be taken into consideration to test the working-hours of a specimen. Numerical simulation could be employed to verify the testing condition, such as the temperature and sound pressure level on the surface of specimen. For a sonic test facility which is designed for hypersonic vehicles, the testing temperature could reach 1480°C on the surface of the test parts, and the overall sound pressure level (OASPL) should reach 170dB1 to simulate the flight condition. In our case, the typical temperature was set to 1200°C (1473K).

Generally speaking, in a sonic fatigue test, high intensity sound is generated by electro-pneumatic loudspeakers, which modulate the frequency and amplitude of sound waves by controlling the speed of air flow. At the testing area, heaters, such as quartz tube heaters, are installed near the specimen to heat up the specimen under investigation. And whether the heat flux between the heater and the specimen will influence the SPL on the surface of specimen is the major concerned problem.

The high intensity sound from electro-pneumatic loudspeakers will yield a base air flow to the reverberation room, which will influence the sound wave propagation in the room and exhaust heat energy from the heater by convection simultaneously. The local air density and the speed of sound vary with the temperature distribution. Numerical simulation under harsh environment is thus a complicated fluid-thermal-acoustic coupled problem(Fig. 2). Simulations of the whole field under multi-physical conditions will encounter two difficulties. One is the expensive computation requirements, the step of time and space need to be fine enough for calculating acoustics field details, but this is unnecessary for fluid-thermal computation. The other difficulty is the setup of the confused boundary conditions, the results will be completely different from real situations because of the ignorance of ambiguous causalities between each two physical elements.

The system was decoupled as follows for simplify the computation. As shown in Fig. 2, the multi-physical field is mainly composed of three parts, fluid flow, heat transfer and acoustic reverberation. First of all, the heat energy solely comes from the heaters, and mainly transfers to the specimen by heat radiation. Considering the fact that air is almost transparent for heat radiation, the air flow will not influence heat radiation between the heater and the specimen. Also the air heat conduction could be ignored because the

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Figure 1. Top view of a reverberation room.

Figure 2. Coupled relationships in the multi-physical model.
coefficient of heat conduction is so small at the working condition when compared to heat convections under a flow speed of several meters per second. As a result, heat convection and heat radiation are the only factors that we need to consider in the thermal model. Secondly, the sound pressure is much smaller than atmospheric pressure. And in such a high temperature of 1200°C, the energy of the sound is a negligible factor compared to heat transfer process. So it is reasonable to assume that the sound will not influence the airflow and heat transfer. Hence, the temperature distribution and heat transfer can be obtained, respectively. Thirdly, since the fluctuating pressure and particle velocity of sound change quicker than the pressure and velocity in the computation of fluid and heat transfer, the velocity and temperature distribution can be treated as stationary background fields when computing the acoustics field. The linearized Euler equations are applied as the governing equation of the acoustics by assuming the sound field is a perturbation of the background flow. The sound due to the flow and thermal field are also negligible when compared to the high intensity horn noise.

The following of this paper is organized as follows. Section II describes the related physical models. Section III introduces the implementations of numerical simulations. Section IV briefly shows some simulation results.

II. Physical Models

In the reverberation room, thermal field, flow field and acoustics field are coupled together as introduced. From the causality of their relationship, system model could be simplified and calculated in order. After computing flow field and thermal field as background physical quantities, acoustics field could be calculated by CAA method.

A. Sound source

In this case, electropneumatic sound generator is used for effective sound generation. An ordinary electropneumatic sound generator is shown in Fig. 3. We have

\[ P = P_0 + p, \quad U = U_0 + u. \]

P and U represent pressure and flow speed at the horn throat; the subscripts of (.)₀ denote those variables at standard atmospheric environment; and p, u represent the acoustics oscillation.

We assume that the sound wave at horn throat is a plane wave, then

\[ \frac{u}{c_0} = \frac{2}{\gamma - 1} \left[ \left( \frac{P}{P_0} \right)^{\frac{\gamma}{\gamma - 1}} - 1 \right], \]

where \( \rho, c \) represent air density and sound speed. The acoustics oscillation and the total pressure had the following relationship,

\[ \frac{p}{P_0} \approx \frac{1}{1 + \frac{c_0}{\gamma \rho_0}} \cos \omega t. \]

The flow velocity \( U(t) \) at horn throat can then be approximated, given the desired sound pressure level (SPL). \( U(t) \) thereafter acts as the fluid boundary condition for the subsequent study. Background flow and temperature field is calculated by OpenFOAM solver, the details of CFD process are omitted for brevity.

B. Acoustics Governing Equation

In a nonuniform background flow, the acoustics field is treated as a perturbation of the air flow field. It is assumed that the sound pressure from the horns is still linear, hence the propagations of sound is governed by the linearized Euler equations (LEE),

\[
\begin{align*}
\frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' \mathbf{v}) &= 0, \\
\frac{\partial \mathbf{v}'}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{v}' \cdot \nabla \mathbf{v} + \nabla \rho' - \frac{\rho'}{\rho_0} + \nabla p' &= 0, \\
\frac{\partial p'}{\partial t} + \mathbf{v} \cdot \nabla p' + \mathbf{v}' \cdot \nabla p_0 + \gamma (\rho_0 \nabla \cdot \mathbf{v}' + p' \nabla \cdot \mathbf{v}_0) &= 0.
\end{align*}
\]
where \( \rho', p', v' \) denotes variables of sound perturbation, and \( \rho_0, p_0, v_0 \) denotes background flow properties, \( \gamma \) is the specific heat ratio of air.

It is worthwhile to mention that LEE could lead to unstable numerical spurious waves in a shear flow.\(^6\) Acoustic perturbation equations (APE)\(^7\) were proposed to address issues. We have implemented both the LEE and APE models in this work. Frequency domain governing equation\(^8\) was also developed for both LEE and APE models. After comparing the simulation results, time domain LEE solver was used throughout the rest of this work for its simplicity and robust performance.

### III. Implementation

For specific simulation we take a group of reference parameters in 2D case and 3D cases. The 2D case is a \( 5 \times 5 \) m reverberation room with two inlets in left-hand side and one outlet in right-hand side, and the 3D case is \( 10 \times 6 \times 8 \) m with six rectangular inlets and on outlet, which is more approaching to real facility scale. In the center of the reverberation room there is a cylindrical and a rectangular pyramid specimen for 2D and 3D case respectively, and plane heaters around it. The heater has a gap in the center for sound wave propagating into it. In our reverberation room simulation, unstructured meshes were adopted to simplify the meshing effects for complicated specimen and heater geometry. Some examples are shown in Fig. 4. Mesh grid number is about \( 6 \times 10^4 \) for 2D case, \( 2 \times 10^6 \) for the 3D cases. And for our special boundary condition setup, extra zones called bufferzone were added to the inlet and outlet.

Spatial scheme is in second order accuracy when solving the partial equations, and one order Euler scheme is used for time marching. Hence, the time step and spatial discretization were set to be very small.
to maintain dispersion and dissipation performance. Higher order schemes are under tests and will be used for the follow-up work.

With the fluid and thermal background generated by flow simulation, we calculate the sound reverberation process of inlet plane wave on several frequencies. The characteristic base air velocity is \( v = 10\text{m/s} \). For many different conditions, we have verified the sound pressure level for the reverberation room. The input sound is a plane wave with a sound pressure level (SPL) at 94dB and with frequencies from 100Hz to 1kHz. A much higher sound input is being tested for a high intensity OASPL in 3D cases.

In these cases general boundary conditions can not ensure a good performance for aeroacoustic computation because mismatching inlet or outlet boundary condition of sound will cause unreal reflection and computation divergence. So bufferzone\(^6,9\) technique was applied at the inlet and outlet regions to satisfy the non-reflect boundary condition. The hard wall condition is applied at other boundaries. Temporal and spatial filters were also used to ensure the stability of the computations, because the high frequency numerical results were generated by mesh or discrete scheme, not by the real physics phenomenon.

IV. Results and Discussions

By comparing the results, we could get some conclusions about characteristic of sound propagation with the LEE model. Without air flow background, APE and LEE’s result are similar and unstable computational circumstances do not appear in our computations using the LEE model. When adding a background flow which contains large velocity gradient or temperature gradient, using APE as governing equation will be more preferable in terms of its stability.

![Figure 5. (a) Velocity magnitude of flow in calculation area, (b) temperature in calculation area.](image)

Figure 5 shows the background thermal-fluid field of the 2D cylinder case calculated by our model. The flow is laminar and the specimen is well heated but the temperature on the surface of specimen is nonuniform. In an empty reverberation room, there are some modal related to sound source frequency. After adding a specimen and round heater board to the reverberation room, we could find that low frequency part are more easily getting into the gap of the heater and reach specimen (Fig. 6(a)(b)), this phenomenon is consistent with physical intuition (sound diffraction). The sound pressure level on the specimen is a little higher with a background flow than that with a stationary background flow. The primitive result shows that background flow will enhance the SPL on the surface of the specimen.

And with the heater warming up the air near the heater and the specimen, it will recede the sound pressure at the surface of the specimen (Fig. 6, Fig. 7). The sound speed will increase when air is heated, then the wavenumber will be less than without heating circumstance. These results are consistent with physics reality which verifies our model is believable.

The geometry of 3D cases is closer to real design. In 3D cases, a rectangular pyramid specimen was adopted and six plate heaters were set around the specimen. A plate shield was set before the outlet for better acoustic reverberation. Following the settings as 2D case, 3D results at different frequencies are obtained as Fig. 8 shows. The center of test section around the specimen and heaters was sliced by Cartesian coordinates for studying sound pressure of test section. Similar results to 2D case shows that the
sound pressure level around the specimen is receded because of heating, so 2D results could be extended to 3D case for quantitative analysis. But for the real complicated 3D specimen geometry, it is necessary to simulate the whole scale simulation if local sound pressure is needed. More 3D cases will be calculated in the follow-up work.

Figure 6. SPL contours, (a) at 500Hz, (b) at 1000Hz, (c) at 125Hz with heater off, (d) at 125Hz heater on, (e) at 500Hz in 1/3 octave average with heater off, (f) at 500Hz in 1/3 octave average with heater on.
Figure 7. SPL curves compared of heater on or off at 500Hz, (a) single frequency, (b) 1/3 octave average.
Figure 8. SPL contours of 3D case at 100Hz, (a) on wall, (b) on y-z plane, (c) on x-z plane, (d) on x-y plane, SPL contours of 3D case at 200Hz, (e) on wall, (f) on y-z plane, (g) on x-z plane, (h) on x-y plane.
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