Coupling problems between solid tube and shock wave / detonation wave

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1 Introduction

When an explosion occurs in a closed vessel, compression waves load its walls and curved area. Large loards will destroy the vessel. Such compression waves show complex behavior in vessel to give further unpredicted causes after interacting with vessel walls. An example is Hamaoka nuclear plant accident occured on November 7, 2001 in Japan. The accident happened in a high pressure and high temperature steam tube. The tube was broken completely by an explosion or may be by detonation because of high pressure hydrogen which was dissociated from steam [1]. We could estimate from the smashed tube materials a size of explosion provided pressure is between 250 to 350 MPa. However such high pressure experiment can not be conducted easily for safty engineering point of views. Hence, instead of performing dengerous experiments, numerical analysis of coupling problem can be suggested for such experimentally difficult cases.

This study will present numerical results of coupling problem between shocked or detonated gaseous phase and solid phase like a wall. The gaseous phase is calculated using our original program and the solid phase is done using Elmer program which is an open source program to solve fluid-solid coupled problem. A case of shock wave propagation in a tube is performed to validate the present numerical system and a case of detonation propagation in a tube is calculated for aplication.

2 Numerical method

The gaseous phase is calculated using our original code for shock wave and detonation wave[2]. Our original program consists of compressible Euler equations with species equations and one-step ethanol/air reaction mechanism [3]. The solid phase is calculated using Elmer open source program. The coupling between the original fluid dynamic program and the Elmer program is semi-strong, which means that the coupling is performed from the gaseous phase to solid phase time by time and is not performed in the opposit way.

The numerical analyses are performed for two cases; the validation using shock wave problem and the application using detonation wave problem. Both calculations are conducted based on the experimental results of Beltman et al. [4] and Tong[5].

2.1 Shock wave and solid wall coupling

To validate the present model for shock-solid wall coupling problem, compressible Euler equations are integrated by 2nd-order explicit Harten-Yee, non-MUSCL, modified-flux type TVD scheme for shock wave-solid wall coupling problem. The experimental work corresponding this problem was performed by Shepherd in 1998. The present numerical work will simulate his experimental results.

The geometry and physical parameters of the test tube is described in Table 1, where the test section has a length of 889 mm and is sealded by the steal of 6.35 mm thickness. The left end of the test tube is connected with the end plate of 12.7 mm thickness. The right end is connected with the transition tube of 260 mm in length, 6.35 mm in thickness, and 50.8 mm in inner diameter. Three strain gauges were set at the middle of the test tube in the interval of 179 mm and three piezo-electric pressure transducers were set at the shock tube and the transition tube in their experiment. The same set-up was applied for the present numerical work.

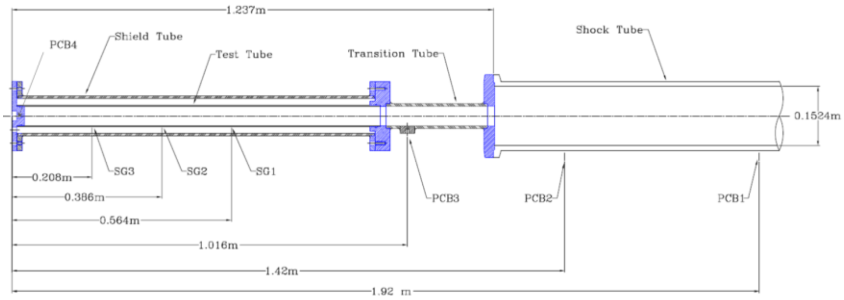

Fig.1 Experimental device by Beltman et al. [4]

Table 1 Geometry and physical properties of the test tube

Radius	26.09 mm	Density	2773 kg/m^3
Thickness	1.601 mm	Poisson ratio	0.33
Length	889.0 mm	Young's modules	72 GPa

The numerical configuration is constructed by coresponding the experimental device[4] as follows:

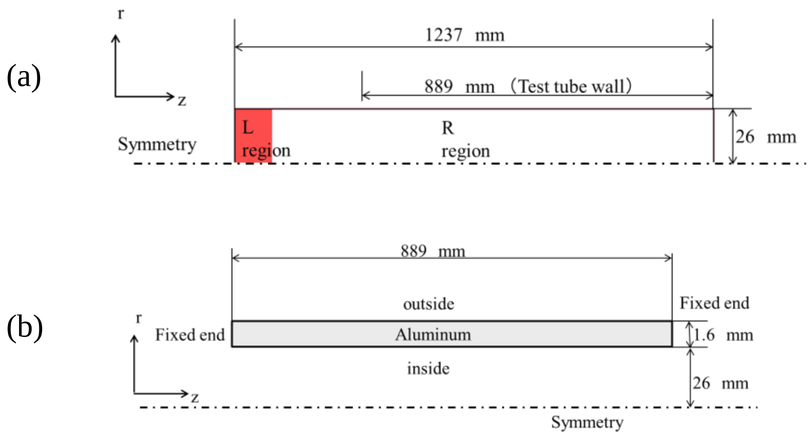

Fig.2 Numerical configuration for shock wave-solid wall coupling problem coresponding experimental device in Fig.1: (a) numerical configuration for gas calculation and (b) numerical configuration for solid wall calculation.

The initial conditions for the gaseous section are shown in Table 2 where L region implies the high pressure section with 10 grid points and R region is provided by the test section condition. Beltman et al. [3] used shock speed as a parameter to classify the experimental results. The present initial pressure in R region is calculated from the pressure obtained by their experimental data together with the shock relations.

Table 2 Initial conditions for the gaseous section

	L region	R region
Gas	He	Air
Pressure	200~600 kPa	6.8 kPa
Temperature	300 K	300 K

The grid systems for these models are described in Table 3 where the grid size is rather coarse of 500 μm.

Table 3 Grid systems for the present numerical case

	Gaseous section	Solid wall section
Grid size [zxr]	$500\ \mu m \times 500\ \mu m$	$500\ \mu m \times 400\ \mu m$
No. of Grid point	131175	8895

The propagating strain wave in solid wall is simulated using above initial and boundary conditions. First of all a typical numerical strain wave calculated in the present problem is shown in Fig. 3 for the case of subcritical condition where the shock speed inside of the solid wall is about 966 m/s. The strain wave has two-wave structure; the precursor wave and main wave. Then the static strain in this case can be measured from the difference in distance between the precursor wave and the main wave as shown in Fig. 3.

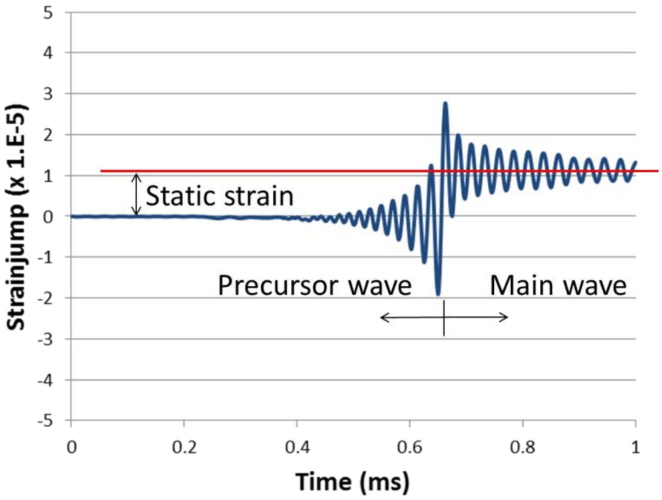

Fig. 3 Profiles of strain wave in solid tube.

The initial high pressure is obtained at the pressure region between 200-600 kPa, while the initial low pressure is set to be constant of 6.8 kPa. The following figure (Fig. 4) is a comparison between the experiment by Beltman et al. [4] and the present simulation for the subcritical case.

The present numerical results show that the dynamic response at the wall loaded from the shock wave has a configuration of static displacement and dynamic wave oscillation. The time of the wave reaching to the strain gauge in the numerical simulation is quite the same as the experimental result. However the amplitude of the experimental case has larger than that of the numerical one because the exact initial high pressure is unknown in the experiments and we set it approximately. Thia approximate value gives some difference in strain jump between the numerical simulation and experimental result.

From these results the present numerical set up is at least qulitatively good comparing with the experimental results by Beltman et al. [4]

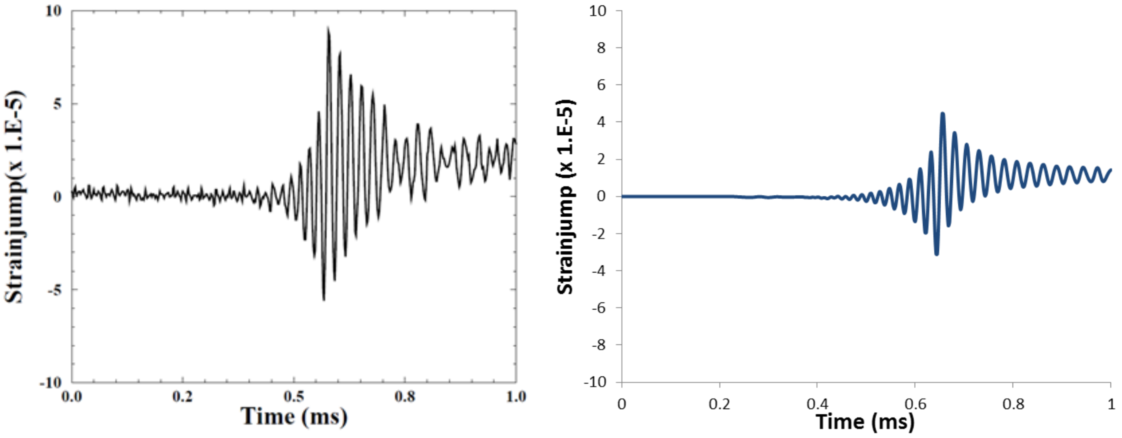

Fig. 4 Comparison of strain wave in steel tube between the experiment (shock speed is 967.8 m/s) [3] and the numerical simulation (shock speed is 966.3 m/s) at the strain gage 2 in Fig. 1.

2.2 Detonation wave and solid wall coupling

The detonation case is numerically calculated applying a detonation tube used by Tong [5] for the detonation-Al tube coupled problem. Tong [5] took the photos of the deformed aluminum tube, but did not show the details of pressure transducer data for non-cracked cases. Most of his experiments are performed with cracked tube beforehand (i.e. making a crack at the first place).

The present numerical configurations of detonation case for gas and solid wall which is made of Aluminum (A6061-T6) are shown in the following Fig.5.

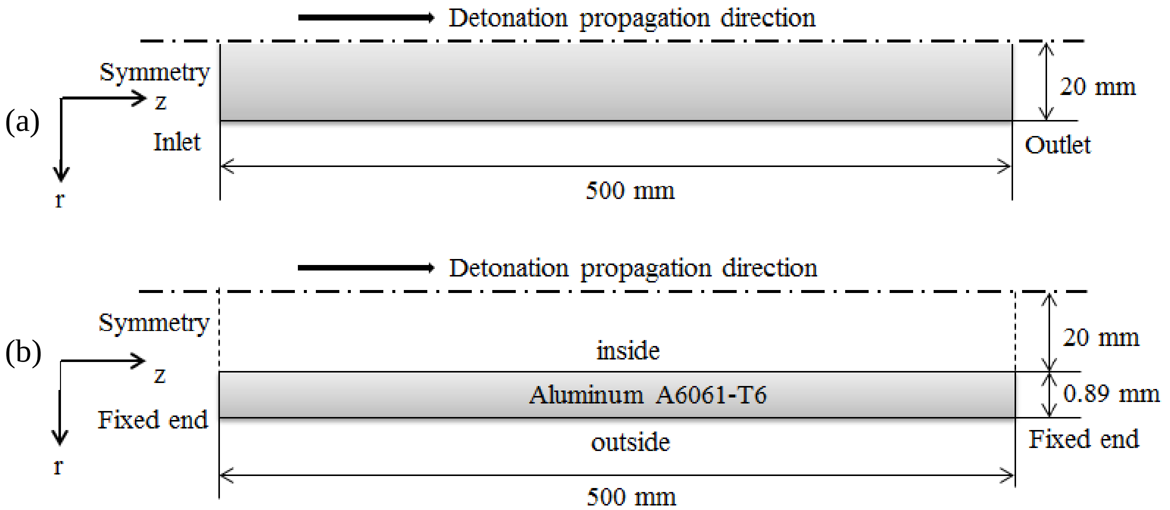

Fig. 5 Numerical configuration for detonation-solid wall coupling problem coresponding experimental device by Tong [5]: (a) numerical configuration for gas calculation and (b) numerical configuration for solid wall calculation.

The geometry and physical properties of the aluminum test tube are shown in Table 4.

Table 4 Size and physical properties of aluminum test tube

Radius	20 mm	Density	2780 kg/m^3
Thickness	0.89 mm	Poisson ration	0.33
Length	500 mm	Young's modules	69 GPa

The calculation is performed using two codes; the original detonation code[2] and Elmer structure code which is Open form, but its chemical reaction parts are not well developed. Hence detonation is calculated using our original detonation code with compressible Euler equations and species equation for ethanol/air mixture. The following tables explain about the detonation code (Table 5), the initial condition for detonation calculation (Table 6), the solid wall structual calculation code of Elmer open source program (Table 7), a boundary condition of pressure (Table 8), and grid system for two codes (Table 9).

Table 5 Numerical system about detonation code

Governing equations	Compressible two-dimensional axisymmetric Euler equations + conservation equations for species	
	5 species(O_2,C_2H_5OH,CO_2,H_2O,N_2), 1-step reaction	
Discretization	Unsteady term	Strang type fractional step
	Convective term	Harten-Yee non-MUSCL TVD
	Source term	Explicit method

Table 6 Initial conditions for detonation calculation

Gas	Ethanol/Air
Equivalence ration	1.0
Pressure	1 MPa
Temperature	298 K
Ignition area temperature	2000 K

Table 7 Numerical system about Elmer code for structual calculation

Governing equation	Two-dimensional axisymmetric elastic equation	
	Solver	Elastic Solver
Discretization	Time-derivative term	1st-order accurate implicit backward differentiation
	Space term	Finite element method

Table 8 Pressure value for boundary conditions

	Outside	Inside
Pressure	1 MPa	Pressure distribution of detonation

Table 9 Grid systems

	Detonation section	Solid wall section
Grid size [z×r]	500 × 500 μm	500 × 300 μm
No. of Grid point	41041	4004

The results of ethanol detonation/alminum solid wall coupled problem are obtained using detonation code and Elmer structure code. Figure 6 shows gaseous pressure profiles and solid wall displacement when detonation propagates in the tube. At the time of 23μs the detonation front is clearly seen and is flactuating as time passes. Meanwhile the solid wall displacement responds faster than the detonation front because of the faster characteristic speed in solid wall. Figure 7 shows a sequential time history of pressure and solid wall displacement. The relation between the gaseous pressure and solid wall displacement is clearly seen. The wall displacement responds much earlier than pressure in the solid wall, then both jump at the same time when the detonation front comes to the wall measurement point. Unlike the shock wave case, the pressure and the wall displacement dicrease like a expansion wave after passing the measurement point. The maximum displacement is 0.025 mm for the pressure of 4.0 Mpa.

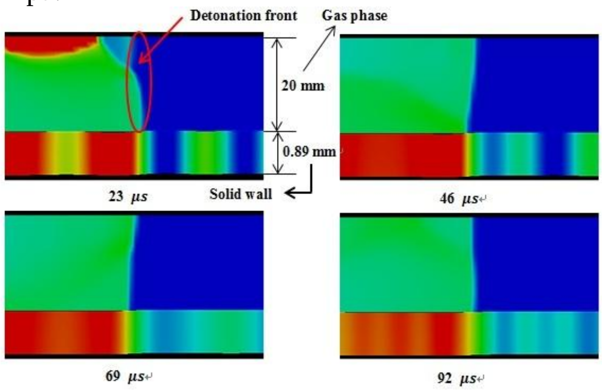

Fig. 6 Gaseous pressure profiles and solid displacement distribution for early four sequential times (23µs, 46µs, 69µs, and 92µs)

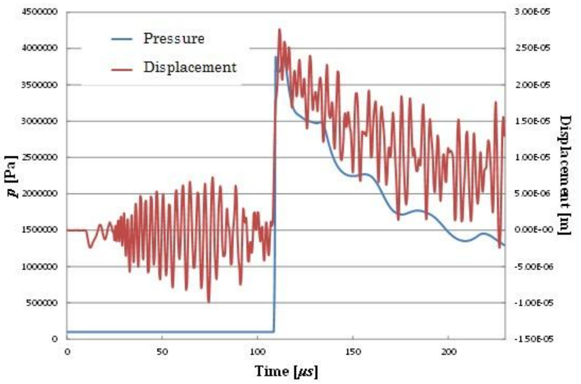

Fig. 7 Sequential time history of pressure (blue line) and solid wall displacement (red line)

3 Conclusions

The coupled problems between high pressure gaseous flow and solid wall of steel and alminum tube are simulated using the original gas flow program and Elmer structure code. First of all the shock wave/solid wall coupling is simulated and compared with the experimental results by Beltman et al. [3]. The numerical results show a qualitatively good agreement with the experimental ones. Especially the timing of appearance from the precursor wave to the main wave agrees well with the experiments. The validation of used programs are applied to the coupled problem between ethanol/air detonation and alminum tube. The results show the similar way of wall displacement behaviour to detonation, but when detonation hits the wall, the wall displacement responds hard and oscilates quickly, then it dicreases as detonation front passes. Althou the present coupling is between weak and strong, the results catch the coupling phenomena well.

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