

UNSTEADY DRAG FORCE MEASUREMENTS OF SHOCK LOADED BODIES SUSPENDED IN A VERTICAL SHOCK TUBE

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Summary Unsteady drag forces acting on bodies suspended in a 300mm×300mm vertical shock tube were measured for shock loading with $M_s = 1.22$ shocks in air and $Re = 7.6 \times 10^6/m$. The test models in which an accelerometer was installed were a sphere, an ellipsoid, rough and smooth cones, a cylinder, a combination of two cones. Unsteady drag forces due to the blast wave generated by detonating a 0.1 g PETN charge in air were also measured. The experimental results were compared with numerical simulations.

Experiments

Shock tube

We used a vertical shock tube of Interdisciplinary Shock Wave Research Center of the Institute of Fluid Science, Tohoku University which consists of four segments as follows. A 2.5 m long and 420 mm/480 mm inner/outer diameter steel tube high-pressure chamber; a 300 mm×300 mm, 5 m long low-pressure channel made of stainless steel; a 1.0 m long test section with a 300 mm×500 mm view field; a 700 mm inner diameter and 1.5 m long dump tank at the end of the shock tube. The driver gas was nitrogen at 240 kPa, producing a shock Mach number of 1.22 in air at 101 kPa and room temperature, with a corresponding Reynolds number of $7.6 \times 10^6/m$. The shock tube cross-section is large enough to minimize the blockage effect of test models of 60 to 80 mm in diameter and the reflected shock wave from the side walls arrived at the model surface after 0.6 ms.

Test model

Test models weighing from 450 g to 700 g were made of aluminum and had various configurations: a 80 mm diameter sphere; cones of 40 degree apex angle and 60 mm base diameter with both smooth surface and grooved surfaces; a 60 mm diameter and 120 mm long cylinder; a 60 mm diameter and 90 mm long ellipsoid; and a double cone consisting of two 45 mm long and 60 mm base diameter connected at their base surface. Each model was suspended vertically from just below the diaphragm section with a 3.5 m long and 1.2 mm diameter steel wire, positioning it at the test section. A compact Endevco piezo-electric accelerometer 2250A-10, sensitivity of 1.02 V/m/s² and resonance frequency of 80 kHz was installed in each model for detecting the vertical component of acceleration during shock loading. Output signals from the accelerometer were taken out via co-axial cable from the rear stagnation point and stored in a high-speed digital memory. In the case of the sphere of about 700g in weight, a shock wave of $M_s = 1.22$ produced a maximum force of about 400 N at 0.1 ms after the arrival of incident shock at the frontal stagnation. The tensile stress wave propagating in the suspension wire took about 0.7 ms to reach the support point and reflected back to the sphere model. Hence the effect of the suspension would first be felt after about 1.4 ms, so that the wire stress was negligibly small, never affecting the measured acceleration (Tanno et al 2003).

Blast wave loading

In addition to the planar shock loading, we tested these models exposed to blast waves produced by the detonation of 0.1 g PETN ignited with a laser-initiated 10 mg silver azide pellet. The stand-off distance between models' frontal stagnation point and the PETN pellet was 200 mm and the PETN had a volume of 50 mm³, small enough to be regarded as point source. The shock Mach number of the blast wave at this stand-off distance was about 1.2.

Flow visualization

In both shock tube and blast wave tests, the interaction of waves with individual models was sequentially observed by double exposure holographic interferometry and also with a high-speed video camera of 1.0×10^6 frame/s at exposure time of 250 ns. Visualization results explained clearly the sequence of dynamic interaction between the moving shock wave and the model surface, producing the measured resulting drag force.

Numerical Simulation

Numerical simulations were performed with a finite-difference scheme solving the axi-symmetric Navier-Stokes equation using turbulent flow modeling (Tanno et al 2003). At first we tested with the sphere model by applying adaptive meshes very densely distributed over the sphere surface. The sensitivity of mesh sizes on the solution convergence was examined. A good agreement between the measured result and the numerical one was obtained for sphere case.

We also solved the Euler equations under the same conditions. The difference between the viscous and the inviscid results was surprisingly small. This therefore implies that at the earlier stage of shock/body interaction, drag forces are generated mostly by the process of wave interaction and the contribution of wall friction and of shear layer effects is very marginal. Hence for other test models we used only Euler computations. The integration of the Euler equations was performed by the finite-difference conservation laws scheme GRP (Ben-Artzi and Falcovitz, 2003). In that scheme the fluxes are evaluated from (analytical) solutions to a Generalized Riemann Problem set up at each cell-interface. The MBT (Moving Boundary Tracking) version with a stationary boundary line was used to implement the surface contour of each model (the Cartesian grid consisted of square cells).

Results and Discussion

Data reduction of force measurement

To evaluate the output signals of the accelerometer, the force measuring system was calibrated by so-called hammering test. The models were impacted with a hammer at their rear stagnation area, whose frequency response was already known. The calibration is based on the concept that from the known time variation of hammer impact force and from the recorded time variation of the acceleration by the model-installed accelerometer, one can deduce the frequency response function of the system. Applying this function to the data recorded in the experiment, we can readily determine the time variation of measured drag forces.

Comparison of measured and numerical results

Excellent agreement between the measured result and numerical one was obtained for the sphere model (Tanno et al 2003) and good agreements were obtained for other models on shock and blast wave loadings (Tamai 2004). In the case of a 80 mm diameter sphere and a 60 mm and 90 mm long ellipsoid at $M_s = 1.22$, drag forces peak at about 0.1 ms after shock impingement and subsequently decrease to a slightly negative value, then gradually approach the steady (positive) drag value. The negative drag force is generated when the diffracted Mach stem of the transmitting shock wave along the model's rear surfaces implodes at the rear stagnation area. This trend agrees well with the wave motions sequentially visualized. The appearance of negative drag force is for the first time confirmed by direct force measurement in a vertical shock tube. The trend of drag forces so far measured differs from that on two-dimensional bodies. In the case of cones and a cylinder, drag forces increase to a maximum value and then decrease monotonically to the corresponding steady drag value, without a negative phase.

Significance of the results

It is interesting to comment on these results in light of the classical d'Alembert paradox, namely the vanishing of drag force in the case of steady potential flow. On one hand we know that in a steady "real" flow the separation in the rear part of the body is responsible for the bulk of the drag force (at high Reynolds numbers). On the other hand, when a flow can be idealized as an unsteady potential flow, the drag is non-vanishing and is explained by the "added mass" effect related to the acceleration of the surrounding fluid. In the case of unsteady compressible flow considered here the transient drag is due to wave interactions. This drag-producing mechanism is decidedly different from all the others, as indicated by the large ratio of about 20:1 between the peak unsteady drag coefficient (about 8 for a sphere) and the corresponding steady value (about 0.4 for a sphere).

References

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