Computational Analysis of the Fluid-Structure Interaction occurring in a model of Two Vehicles Overtaking Each Other

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Outline

(1) Introduction and the aim
(2) Governing Equations
(3) The model designs
(4) The Computer Simulation Results
(5) Discussion
(6) Conclusion

Introduction

(1) Aerodynamic problems such as a high air resistance to the car movement, vibration of vehicles, excessive pressure fluctuation and noise generated inside the car.

(2) Air flow around a moving car at high speeds.

(3) The ride quality is very important.

(4) The aerodynamic forces and their effects.

The aim

To investigate the impact of aerodynamic effects on two Ahmed body geometries overtaking each other in order to improve the ride quality and reduce the energy consumption.

Governing Equations

Navier-Stokes equations

The transport flow variables are governed by two basic physical principles:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0. \qquad i = 1,2,3 \qquad (1)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (u_i \rho u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} - F_i = 0 \qquad i,j = 1,2,3 \qquad (2)$$

where:

ρ is the mean mass density of air.
F_i represents the body forces.
τ_{ij} is the shear stress in the fluid.
p is the pressure.
u_i is the air flow velocity.

Governing Equations

the hybrid $SST\ k - \omega$ turbulence model

It is used to solve the aerodynamic coefficients during an overtaking event of two bluff bodies

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \widetilde{P_k} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_k \frac{\rho k}{\omega}\right)\frac{\partial k}{\partial x_j}\right]$$

(3)

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho\omega u_j)}{\partial x_j} = \alpha\rho S^2 - \beta\rho\omega^2 + 2(1 - F1)\sigma_d \frac{\rho}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_\omega \frac{\rho k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] \qquad i, j = 1,2,3 \qquad (4)$$

where: P_k denotes the production limiter; $\beta, \beta^*, \alpha, \sigma_\omega, \sigma_d, \sigma_k$ denote the closure coefficients in the turbulence-rate equation to be **0.075, 0.09, 0.55, 0.5, 0.856 and 0.85**, respectively; μ denotes the dynamic viscosity; S denotes the strain rate; $F1$ is the first blending function.

Governing Equations

The lagrange's approach

The impulse conservation equation below has been developed by using the Lagrange's approach. It can be solved by using one of the FEA approaches.

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F_i(t)\} \quad (5)$$

where: $[M]$ denotes the mass matrices for the body, $[K]$ and $[C]$ are the system stiffness and damping matrices, $\{\ddot{x}(t)\}, \{\dot{x}(t)\}$ and $\{x(t)\}$ represent the system acceleration and displacement vectors at time t. The fluid forces are denoted by $\{F_i(t)\}$.

The Computational Fluid Dynamics (CFD) workflow process

(1) Creating the geometry (*SolidWorks*)

(2) Creating the mesh domain (*BlockMesh and snappyHexMesh utilities*)

(3) Setting up the case study (*OpenFOAM*)

(4) Simulation run in parallel on a number of cores (*OpenFOAM*)

(5) Evaluation of results (*ParaView*)

The model design

(1) Simplified CAD design

(2) the slant angle is 30° and the vehicle dimensions are (73.8, 27.3 and 20.16 cm) as the length, width and height, respectively.

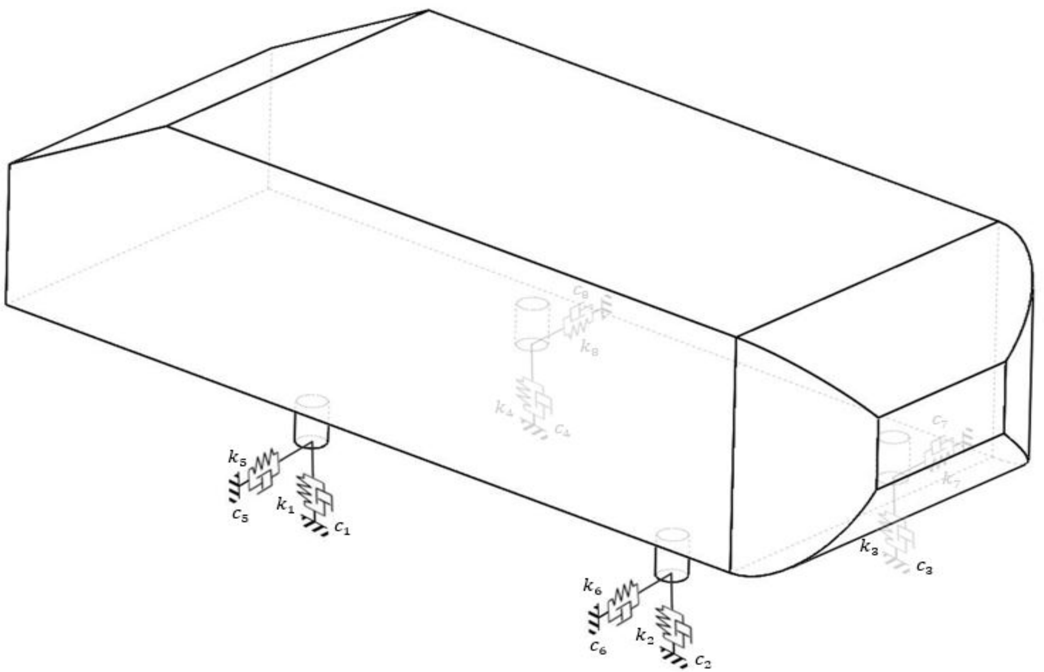


Figure 1. Schematic layout of the multi-body dynamic system of the Ahmed body model

The assumptions

(1) 3-dimensional incompressible flow.

(2) The structures are treated as elastic bodies.

The Computer Simulation

(1) Finite Volume Method (FVM) to solve the fluid dynamics.
(2) Finite Element Method (FEM) to solve the structure dynamics.
(3) The wind tunnel width is 8 meters.
(4) A dynamic mesh has been used in this case.
The total mesh volume after using the snappyHexMesh technique was 17,119,330 cells

$$Re = \frac{\rho V L}{\mu} = 3.9 \times 10^5$$

where:
ρ: the air density ($1.2041\ kgm^{-3}$) (at 20 °C)
V: the lift car velocity ($30.32\ ms^{-1}$)
L: the Ahmed body width/depth (2 m)
μ: the dynamic viscosity of air ($1.81 \times 10^{-5}\ kgm^{-1}s^{-1}$)

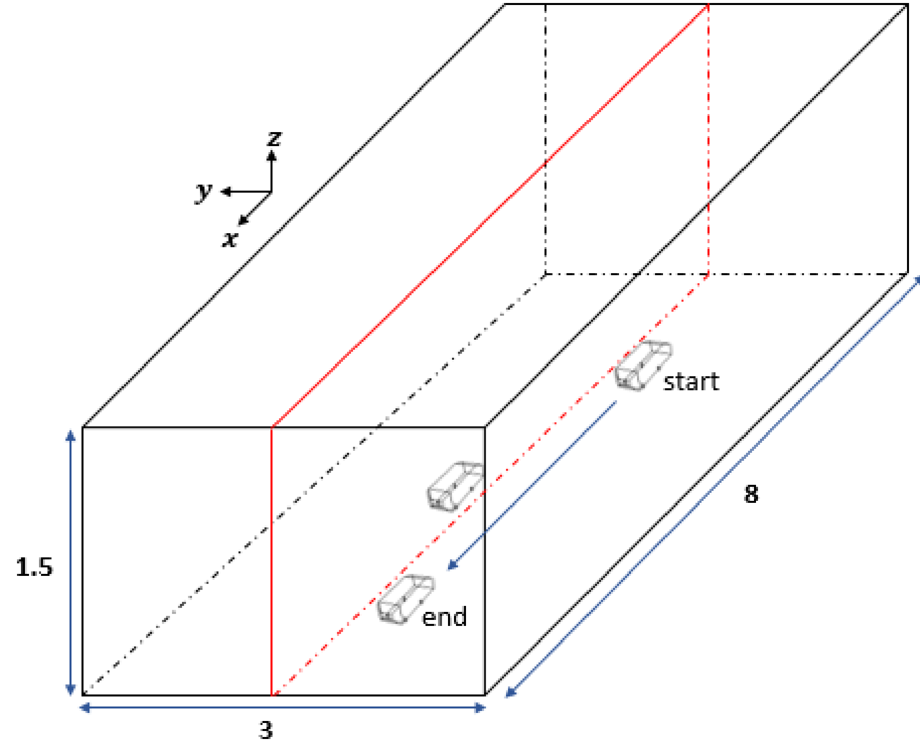


Figure 2. Cross-sectional area of the simplified cars/hoistway model (top view), all dimensions in mm

CFD mesh generation

(1) BlockMesh utility has been utilised to generate a simple block consists of **81000 cells** which are fully structured as a hexahedral mesh.

(2) A dynamic mesh has been used in this case.

(3) The total mesh volume after using the snappyHexMesh technique was **17,119,330 cells**.

(4) The wall layers have been added on both car structures and all boundary conditions to have a better prediction to the flow near wall.

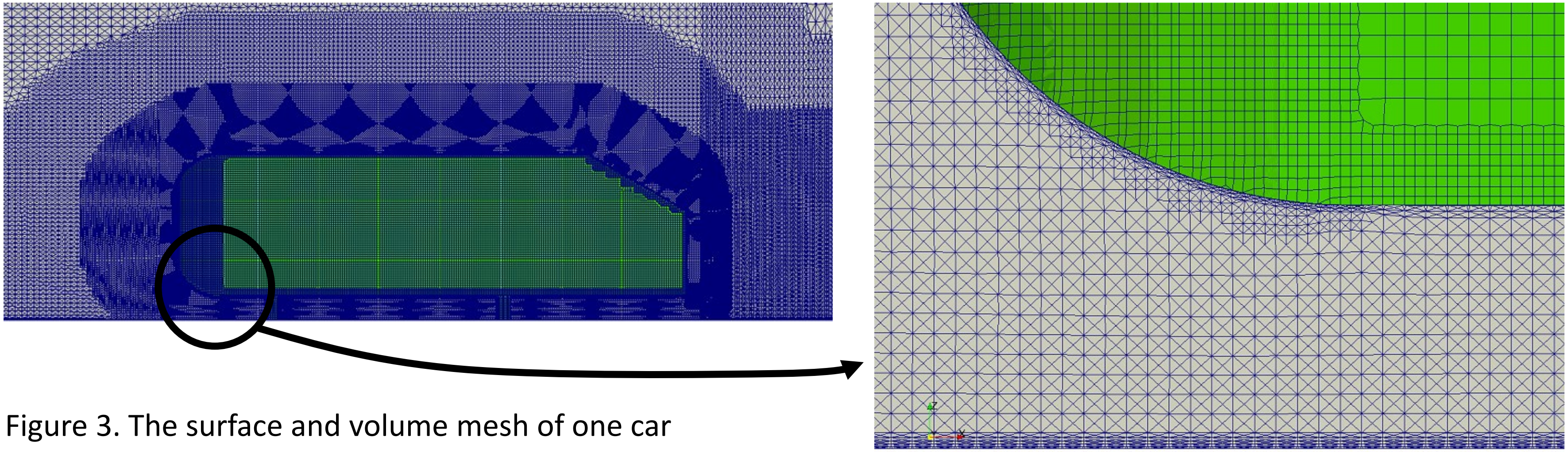


Figure 3. The surface and volume mesh of one car

Dynamic mesh deformation

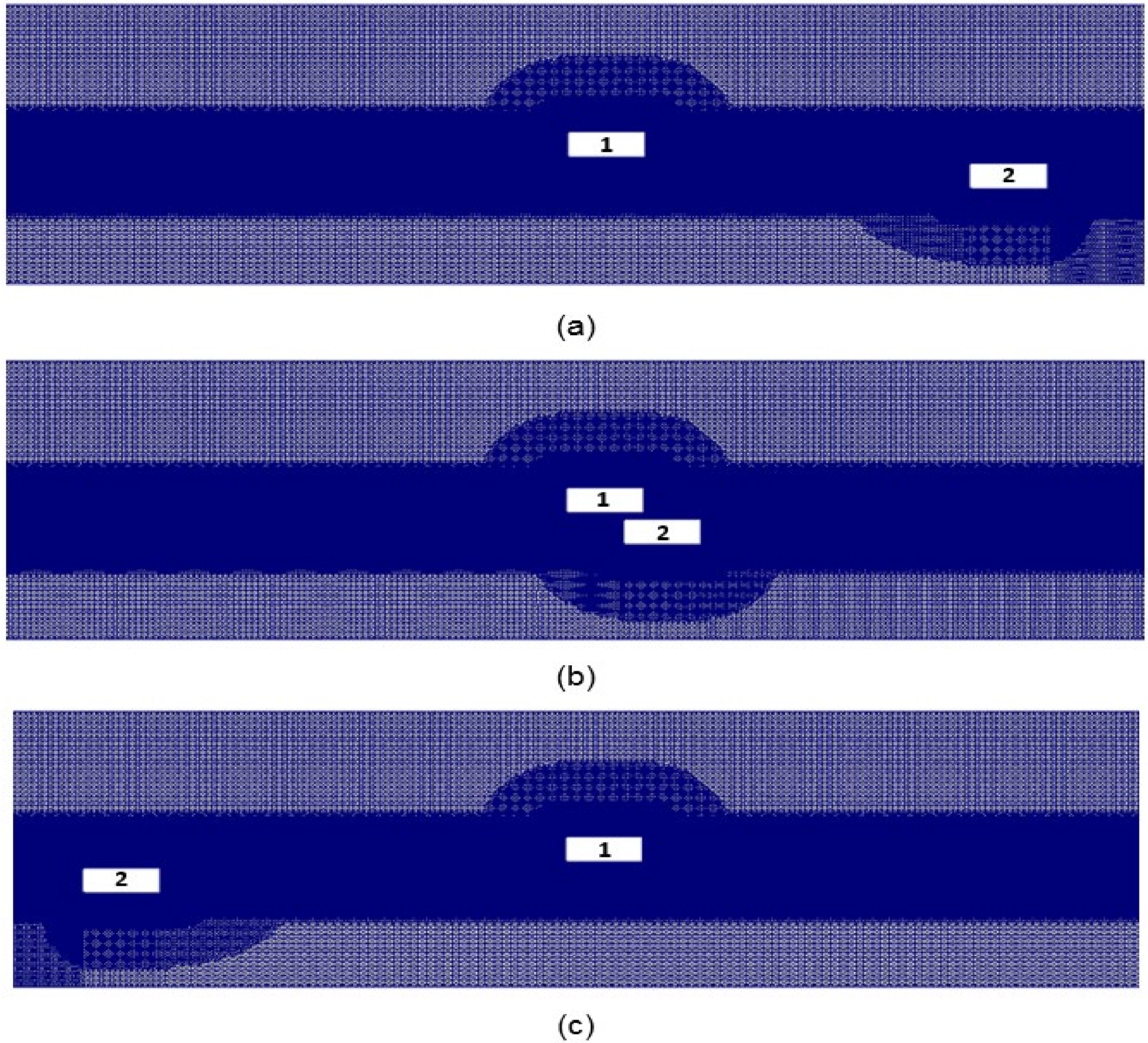


Figure 4. The computational mesh deformation for the overtaking manoeuvre. (a) Start, (b) at the overtaking event, (c) end.

The FEA dynamic scenario

- Processing the input data.
- Preparing Model topology data.
- Generating the model matrices.
- Assembling system matrices.
- Computing the normal modes and residual vectors has already being done in the modal analysis.
- Processing external loadings (the fluid excitation).
- Applying rigid-body constraints.
- Solving for unknowns.
- Generating model results.

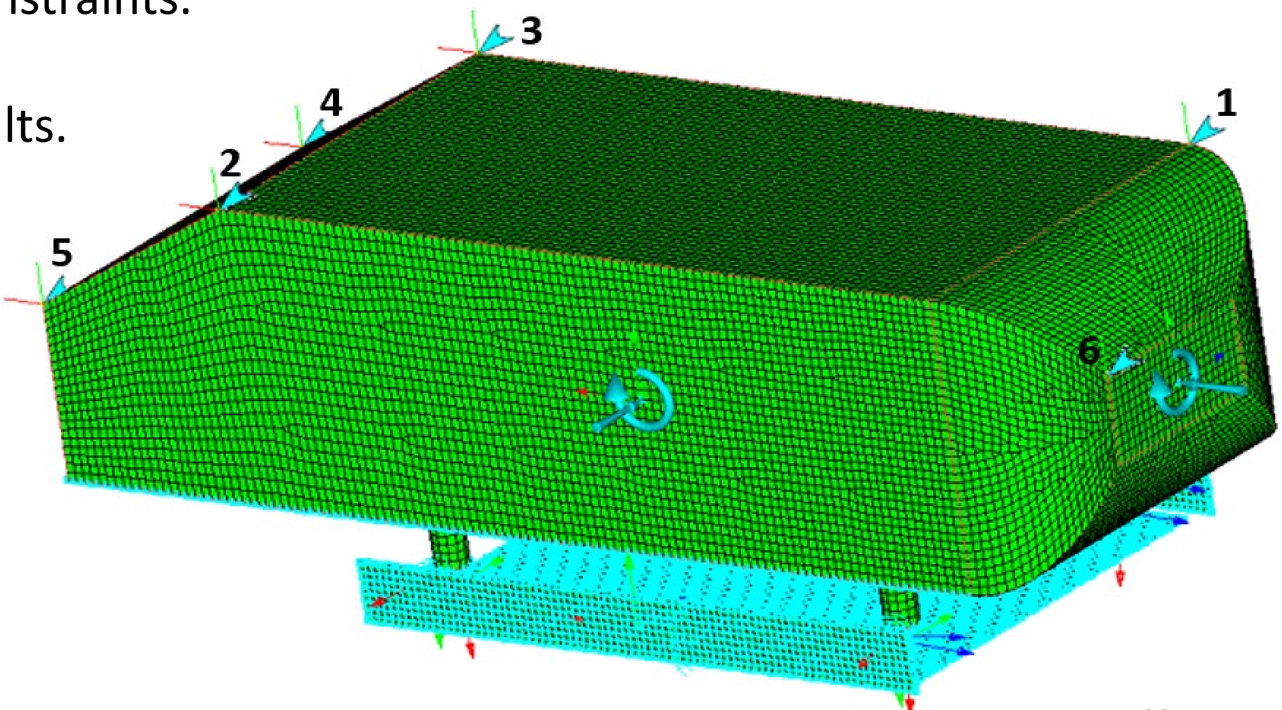


Figure 5. The location of dynamic loads and six sensors.

Results and Discussion

CFD results

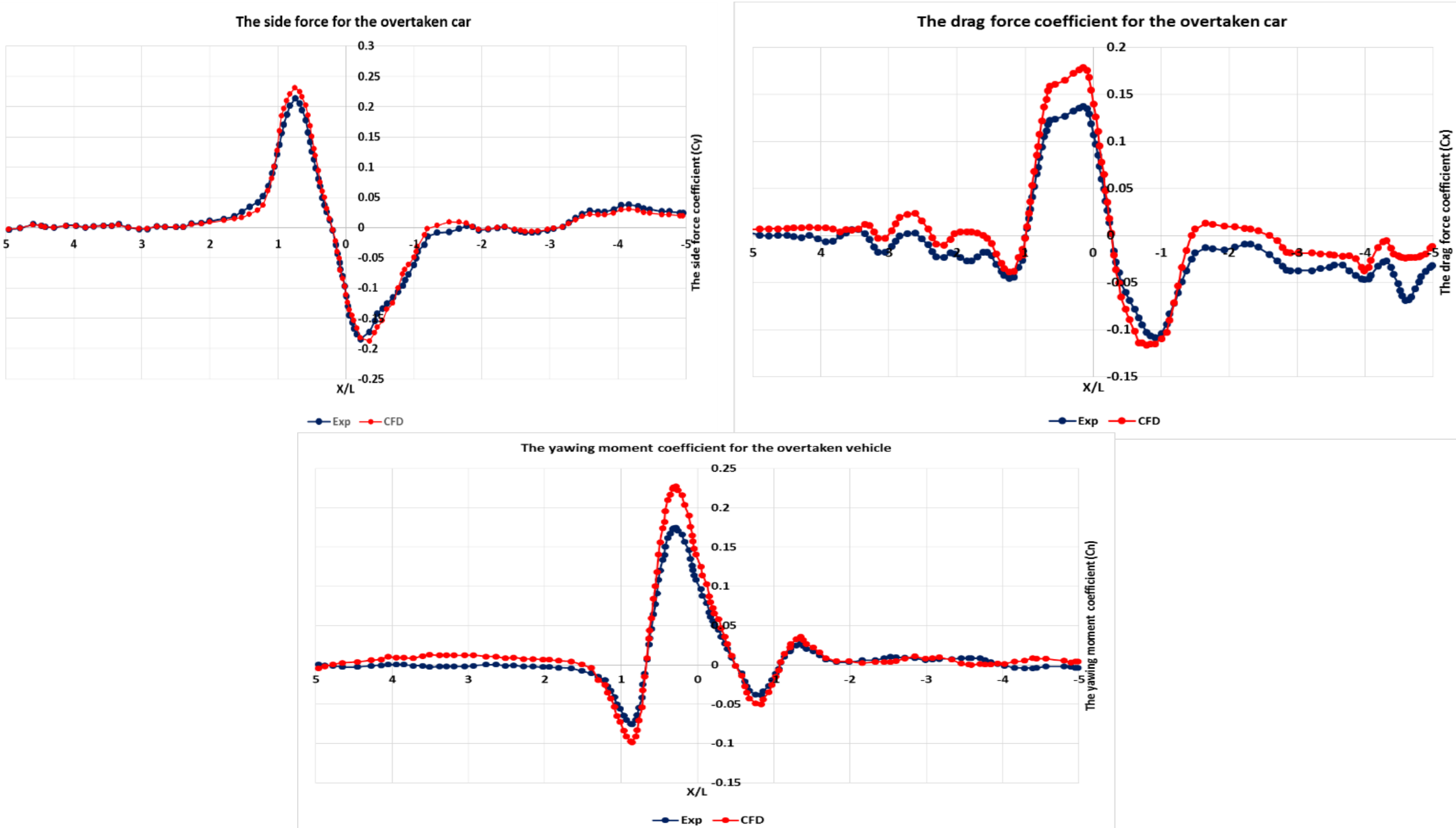


Figure 6. The aerodynamic coefficients comparison between the numerical and experimental data.

Results and Discussion

CFD results

The pressure coefficients were obtained by using the equation below:

$$C_P = \frac{P - P_\infty}{0.5\rho U^2}$$

Where: C_P denotes the pressure coefficient, $P - P_\infty$ is the relative pressure.

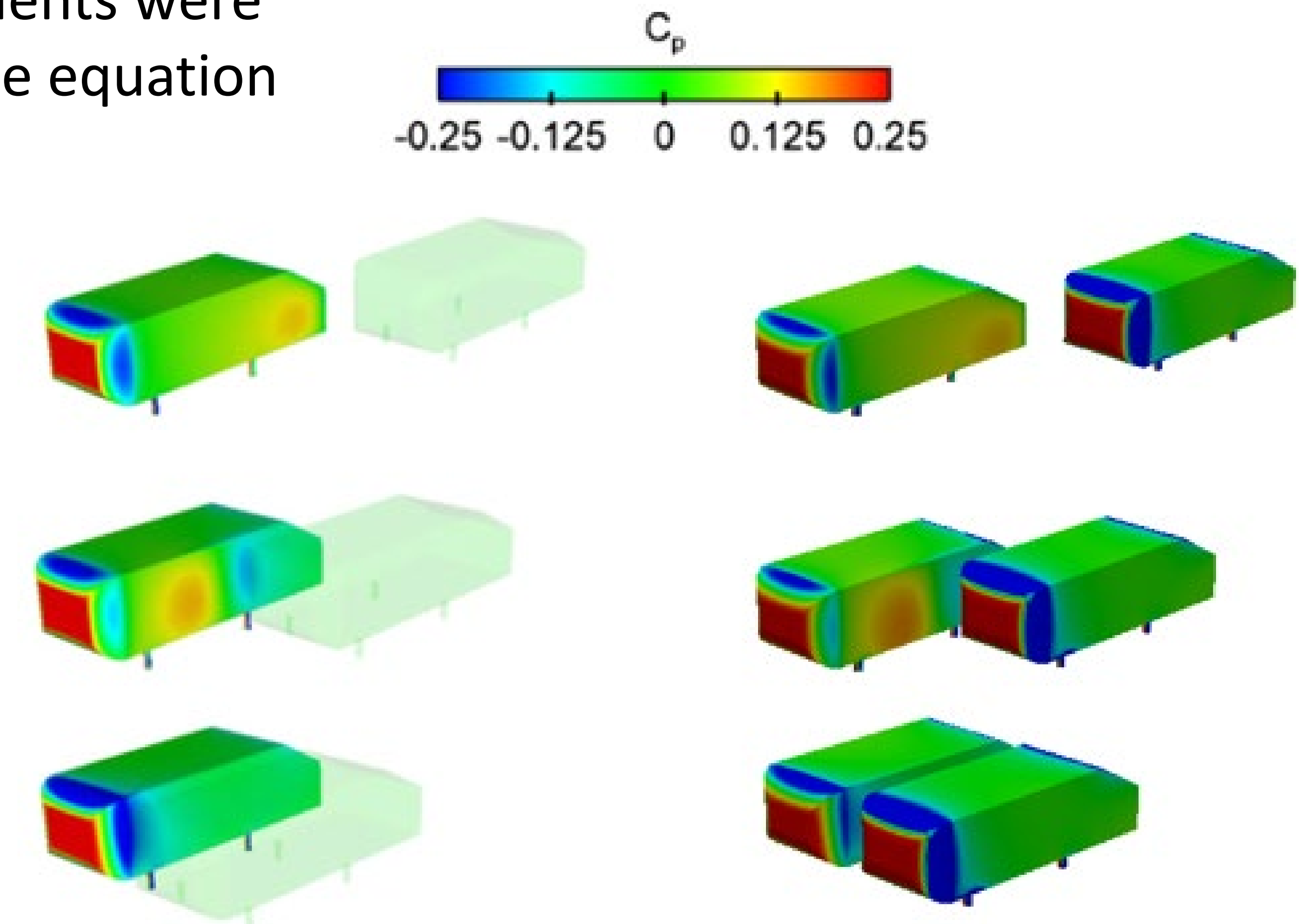


Figure 7. The comparison between two CFD data; CFD data from the open-source code used in this work (right); CFD published data (left)

FEA results

A finite element model was built by using a commercial software which is a powerful tool for simulating linear vibration analysis. The FEA software was also used for results visualisation. The stationary was modelled as a fully deformable body made of aluminium and the thickness is set to be 5mm.
The table shown illustrates the natural modes of the Ahmed body oscillating system. The natural frequencies are calculated depending on the structure, material and boundary conditions.

Table 1. The natural modes and their natural frequencies

Mode	Natural frequency (Hz)
1	0.276
2	0.759
3	1.16
4	1.21
5	1.96
6	2.62
7	132
8	202
9	216
10	258
11	292
12	312
13	374
14	391
15	421
16	469
17	527
18	788
19	1100
20	1.5×10^6
21	2.64×10^6

The fully dynamic response at the 3rd mode = 0.34cm

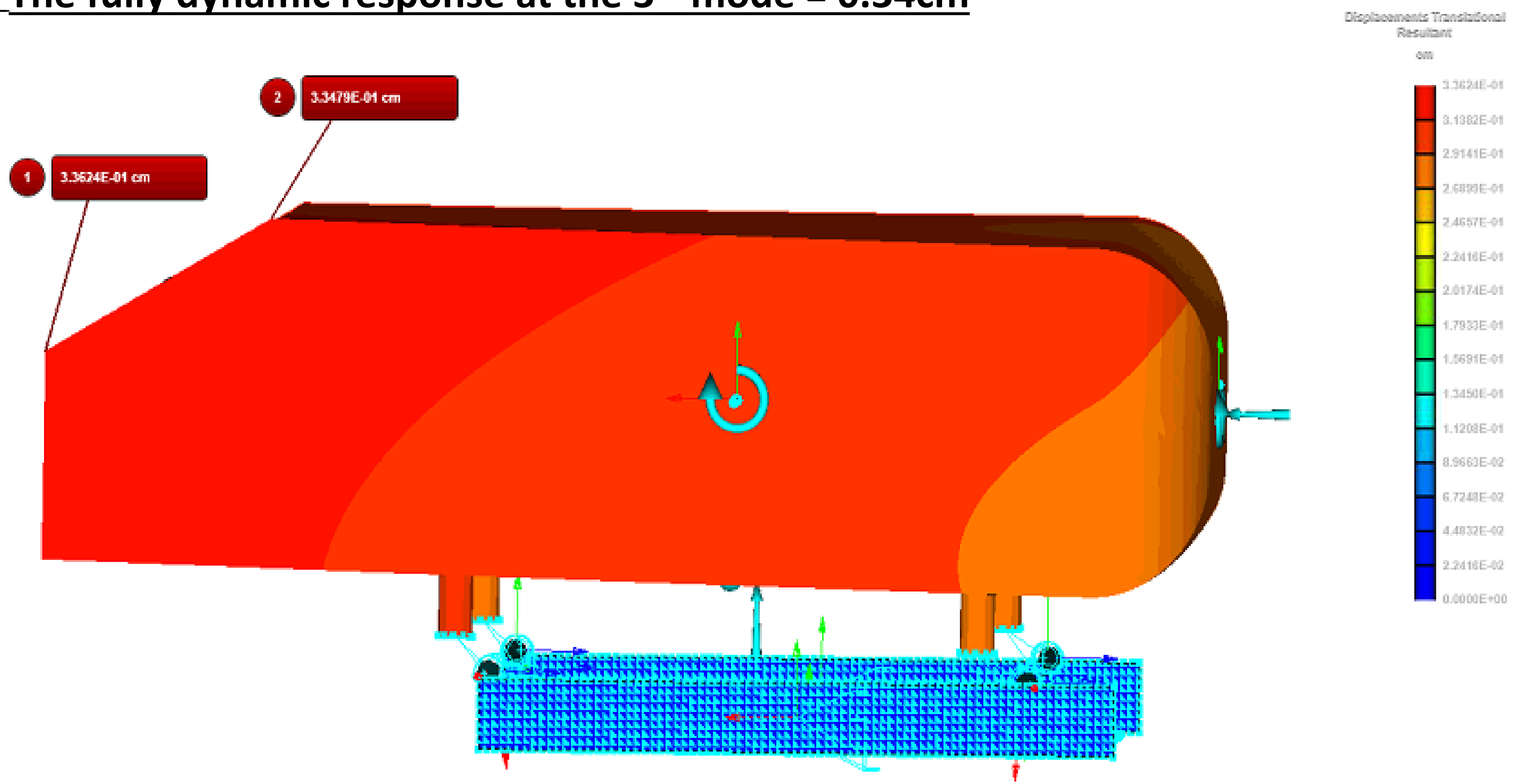


Figure 8. the 3rd mode

_The fully dynamic response at the 5th mode = 0.19 cm

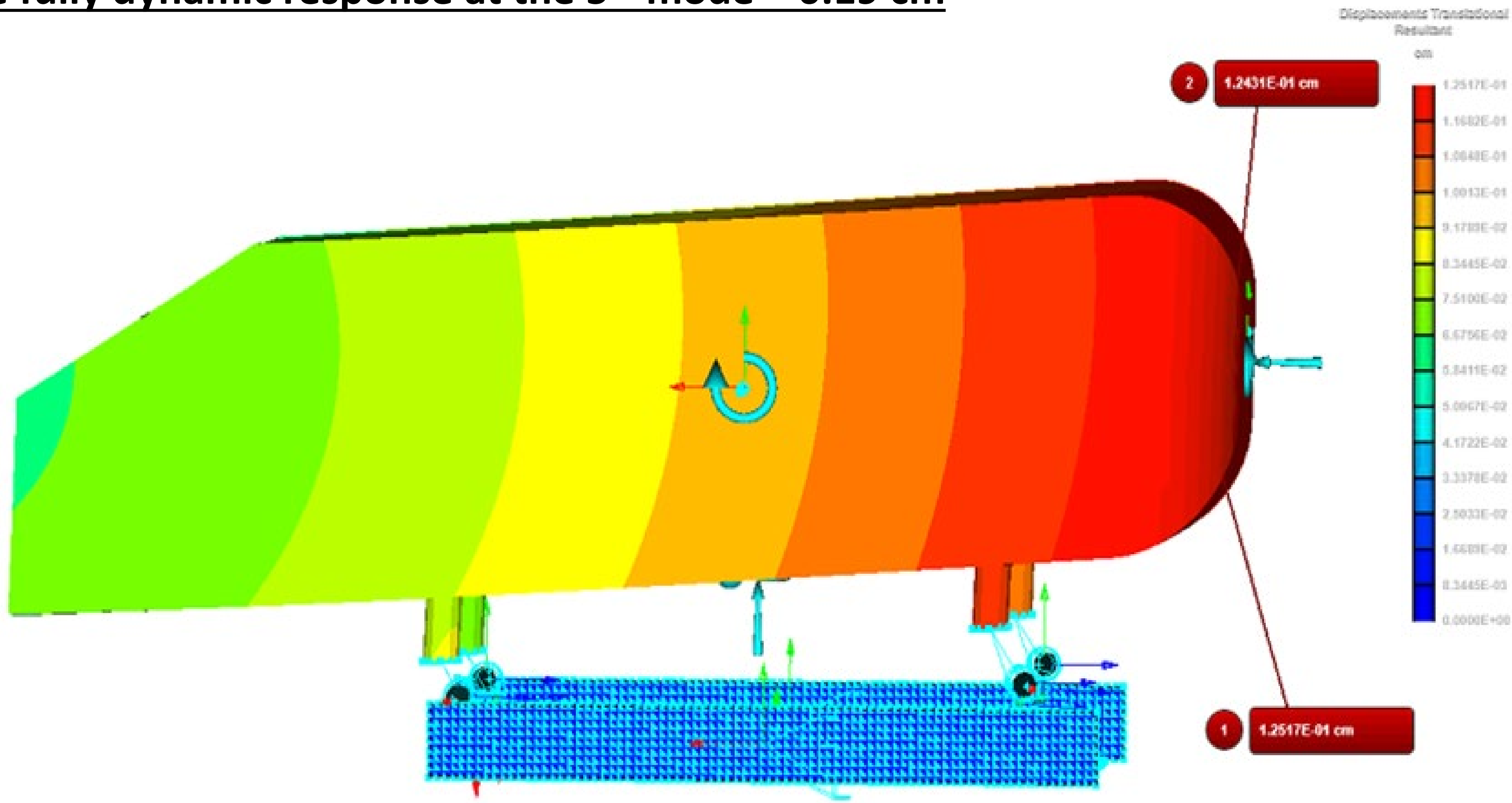
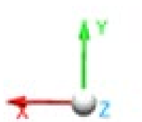


Figure 9. the 5th mode



<u>The fully dynamic response at the 7th mode = 7.9×10^{-5} cm</u>

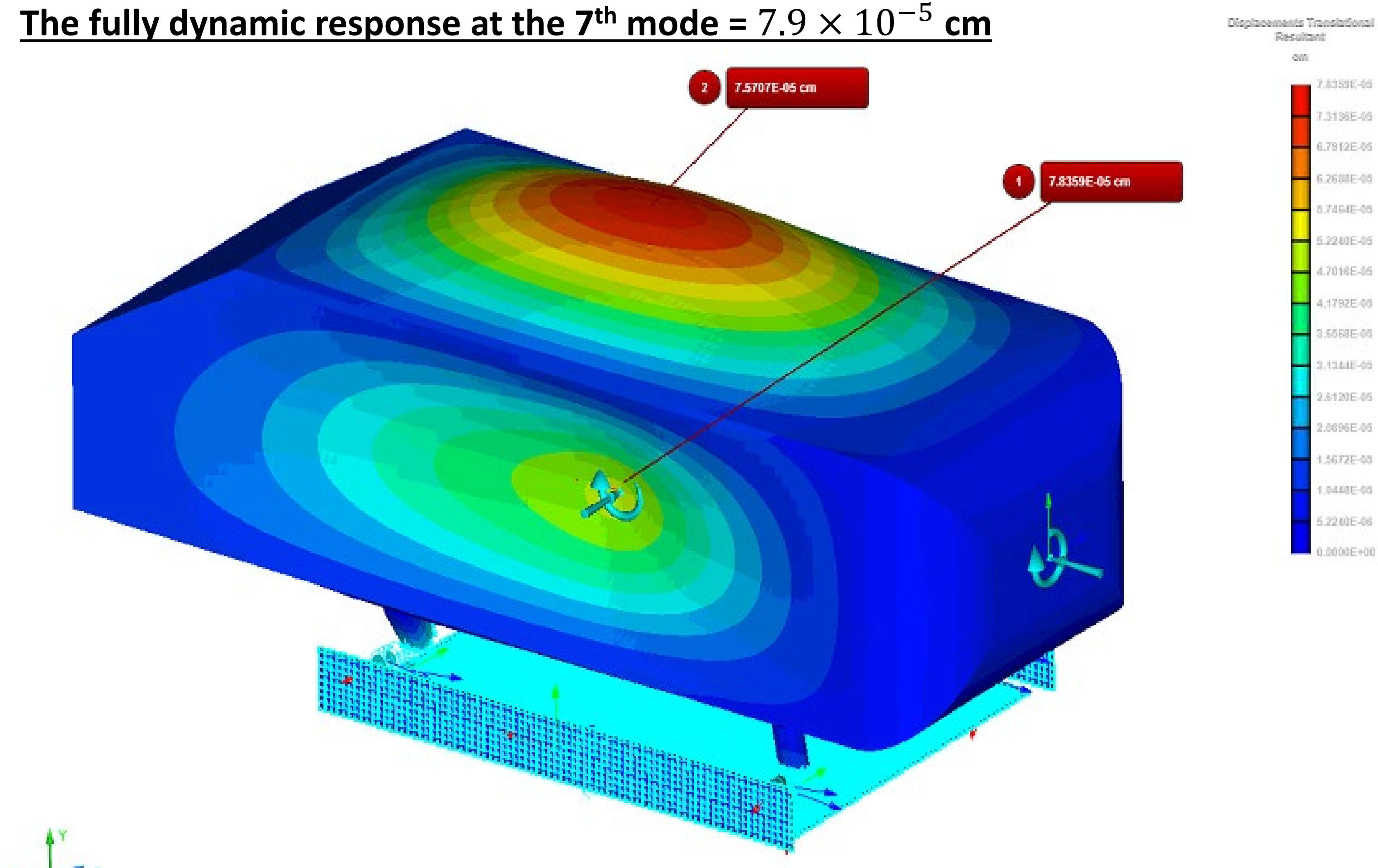


Figure 10. the 7th mode

<u>The fully dynamic response at the 7th mode = 7.9×10^{-5} cm</u>

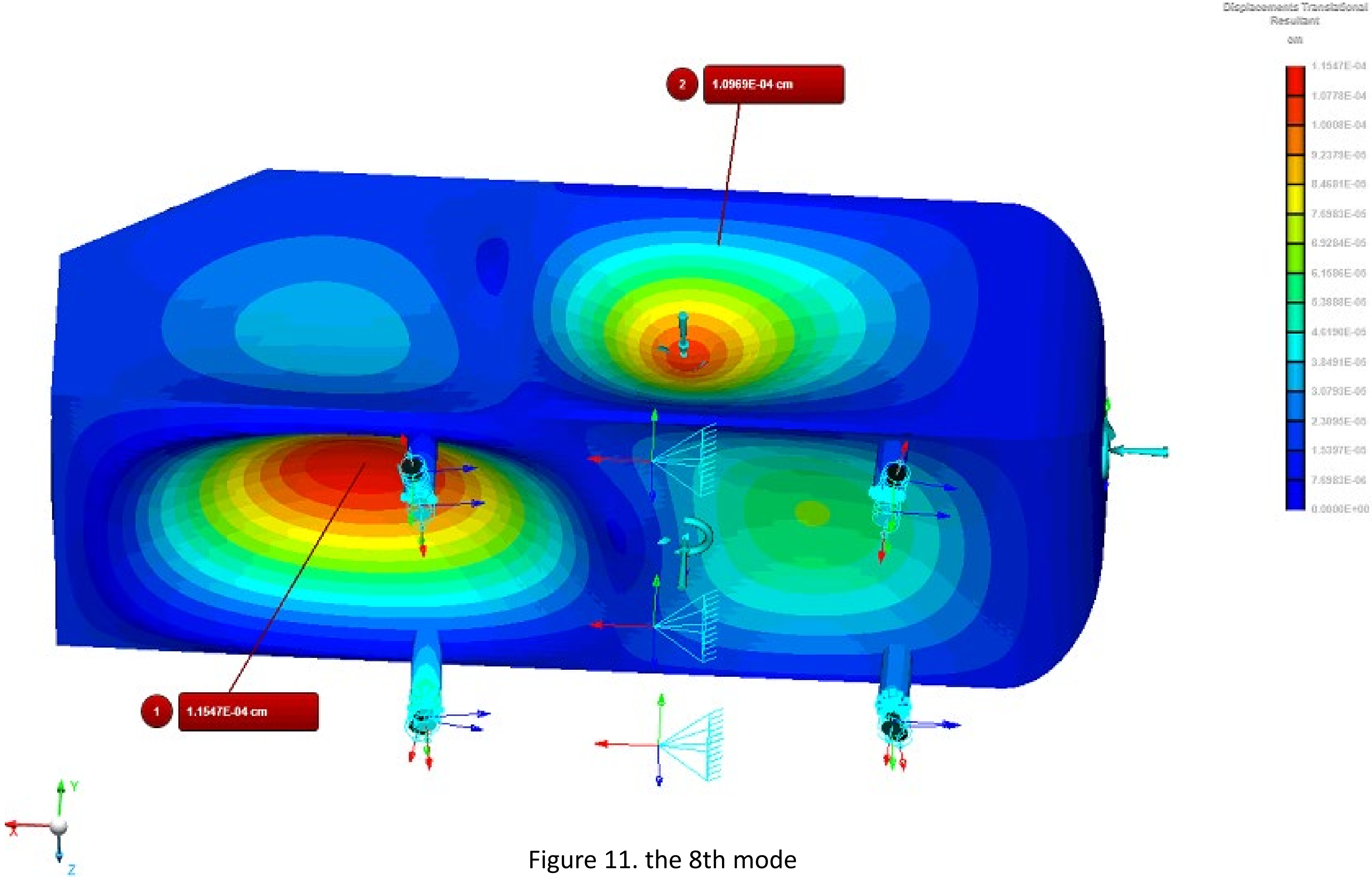


Figure 11. the 8th mode

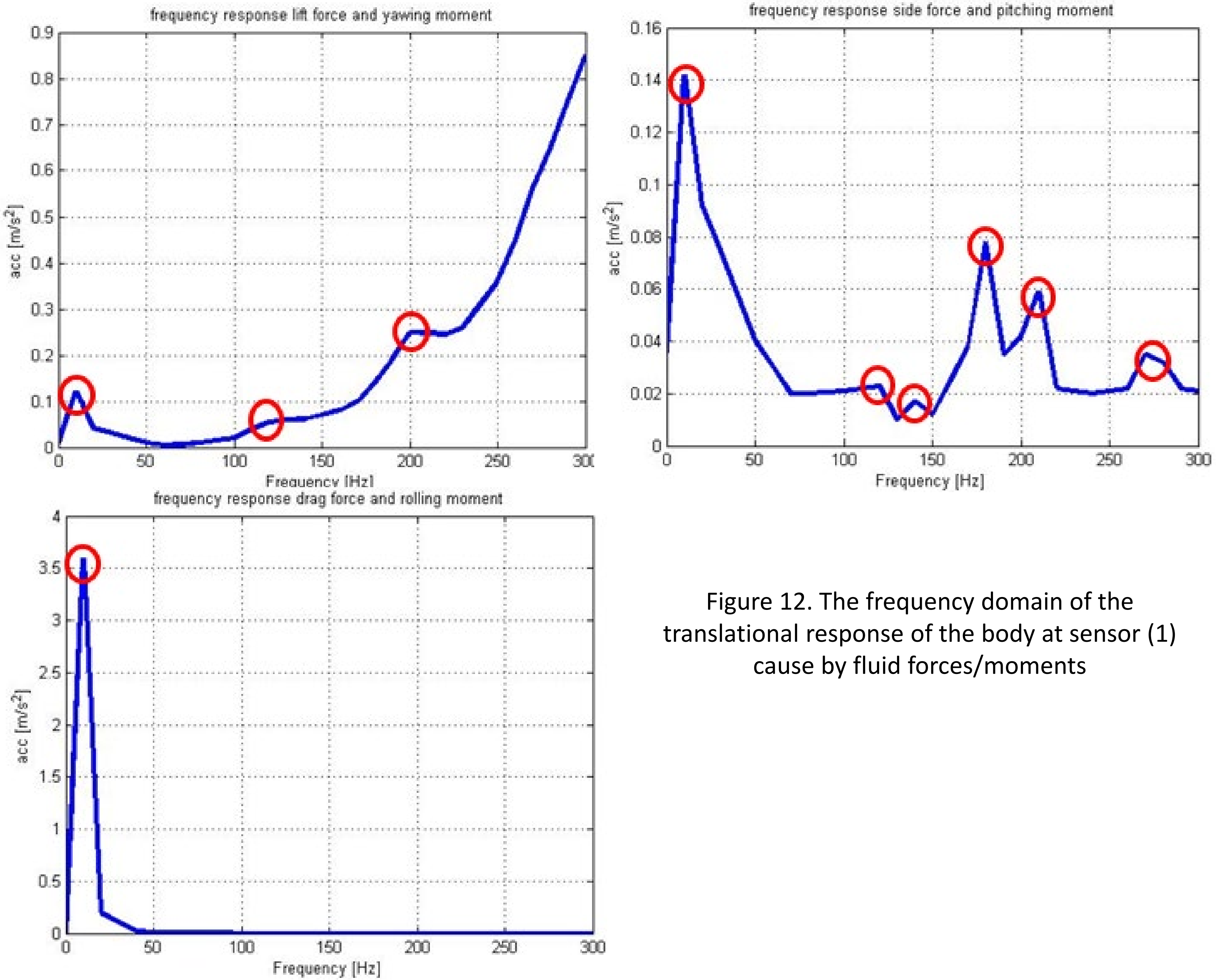


Figure 12. The frequency domain of the translational response of the body at sensor (1) cause by fluid forces/moments

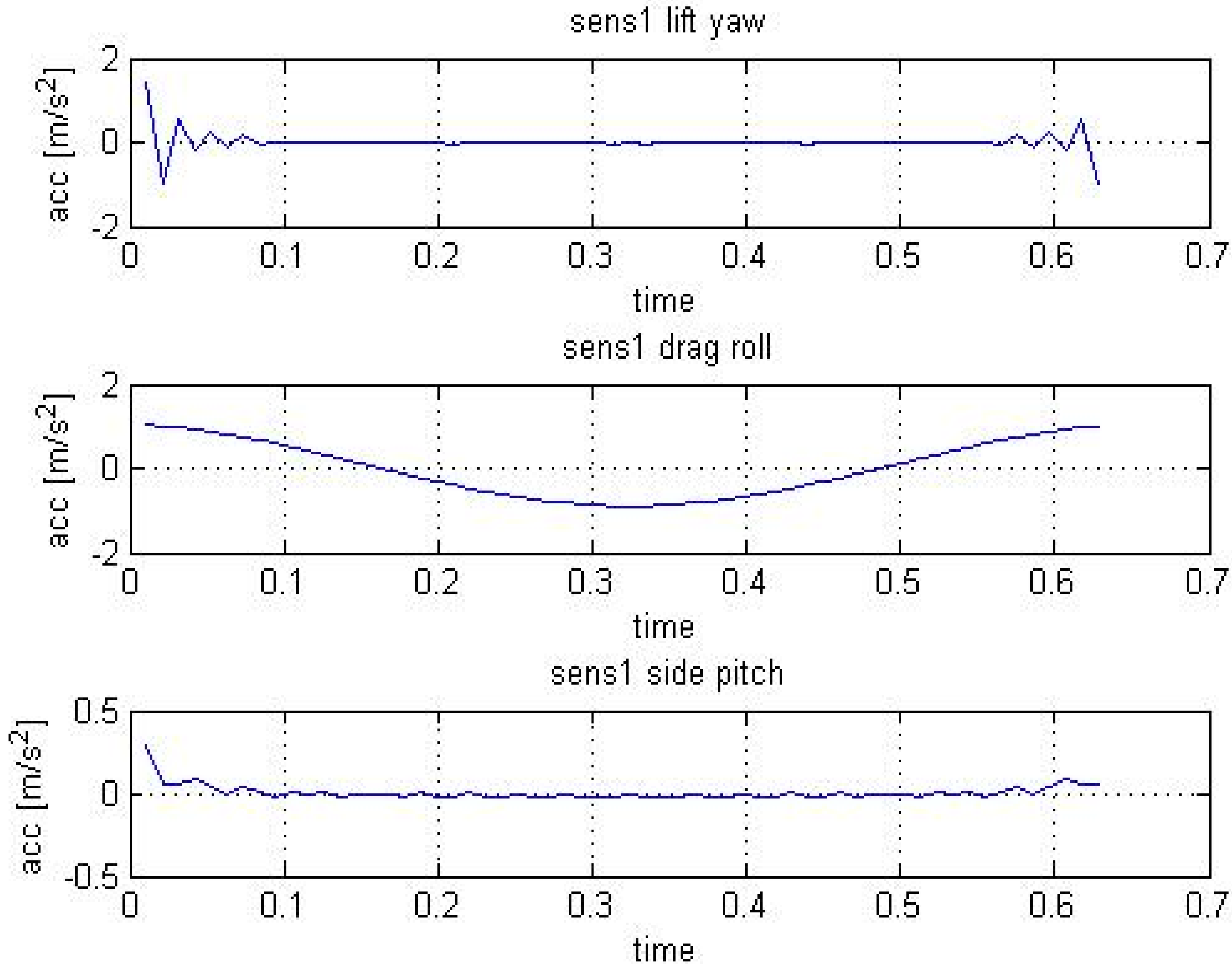


Figure 13. The time domain of the translational response of the body at sensor (1) location for the dynamic fluid excitations.

The Conclusion

(1) The transient effects of fluid structure interaction of a freely vibrating Ahmed body has been discussed in the presentation.

(2) The scenario applied involves two cars are overtaking each other in the same wind tunnel.

(3) CFD and FEA have been used to test the aerodynamic loadings and their influence on the vehicle vibration.

(4) It was revealed that the fluid dynamics has a significant contribution to both the stationary and the moving cars.

(5) The transient phenomena is very important in terms of structural dynamics.

(6) This study has proved that designers should consider the aerodynamic effects and make useful improvements to mitigate their effects.

Thank you

Any questions ?