Calculation of HF Eigenmodes in Liquid Rocket Combustion Chambers

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Abstract: This document describes the application of COMSOL Multiphysics to the calculation of high frequency (HF) eigenfrequencies and eigenmodes in liquid propellant rocket combustion chambers. These eigenmodes are acoustic oscillations of the fluid present in the combustion chamber. The oscillation is fed by the combustion process. The environment is characterized by high mean flow velocities.

Keywords: High Frequency Combustion Instability, Rocket, HF, Simulation

1. Introduction

1.1 Rocket Engine Combustion

Liquid propellant rocket engines provide the thrust to lift rockets into space or to position satellites. Their thrust level reaches, depending on the size, from fractions of Newtons of close to equivalents of 1000 metric tons. Fuel consumption can reach the range of a ton per second. The combustion system is characterized by a very high power density – the power of a nuclear power plant in a volume of fractions of a cubic meter. This power is provided by a combustion process which is fed continuously through the injection system.

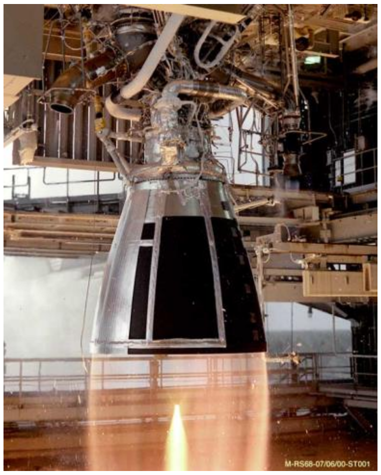

Figure 1. An RS-68 rocket engine on the test bench (source: [1])

The combustion process usually takes place in a cylindrical combustion chamber which operates at pressure levels from some 10 bar to more than 200 bar. This pressure is discharged through a convergent - divergent nozzle and accelerated to supersonic speeds. The momentum of the exhaust gas is then producing the thrust [2]. The most visible part of the rocket engine usually is the large convergent part of the nozzle (see Figure 1).

1.2 Combustion Instability

Keeping in mind the high energy release rate, it becomes clear that already a small percentage of fluctuation in this combustion process constitutes a large fluctuating quantity. The fluctuations of the combustion process lead to acoustic perturbations which are reflected in the volume of the combustion chamber.

If the combustion process couples back to these acoustic fluctuations, combustion instability can arise.

These combustion instabilities oscillate with the combustion chamber's acoustic eigenfrequencies.

The basic eigenmodes can be characterized by the types of eigenmodes present in cylindrical domains (Figure 2).

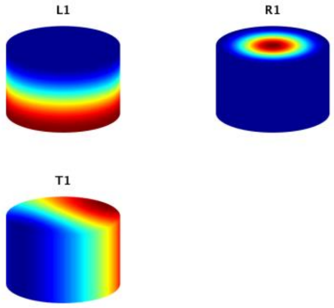

Figure 2. Typical 1st order eigenmodes of a cylindrical domain

Combustion instabilities are capable of destructing combustion chambers in fractions of seconds. Typically, the failure occurs due to thermal overload due to drastically increased heat transfer and a disturbed combustion zone. (see Figure 3) [2].

The most prominent example of an engine suffering from combustion instability is the Rocketdyne F1 engine which took more than 2000 full scale tests until a stable configuration was achieved. [4]

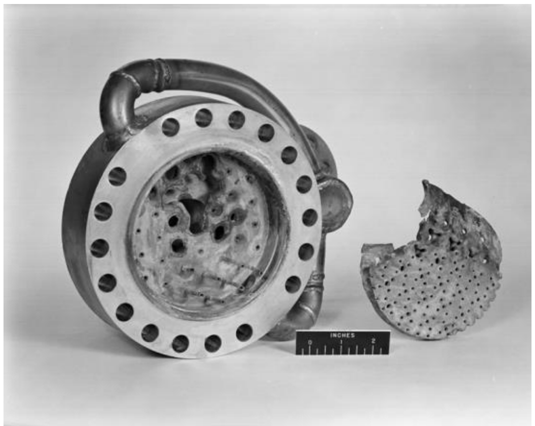

Figure 3. Typical thermal damage to a liquid propellant rocket injection head (source: [4])

Still today, combustion instability can pose severe delays to development programs. Quick and reliable calculation of the combustion chambers eigenfrequencies is a first and vital step to assess the stability properties of combustion chambers.

1.3 Acoustic Environment

Naturally, the conditions present in a rocket combustion chamber differ from the ambient conditions found for many acoustic applications.
There are considerable gradients due to the combustion process, the gas composition is variable and the mean flow can take values of the sonic velocity.
Since these conditions exceed the capabilities of most acoustic solvers, simplifications have to be made for the mean flow field and for the nozzle.

In the following, a series of calculations is presented which step by step assess the capabilities of the built in acoustic solvers of COMSOL for the given application.

2. Use of COMSOL Multiphysics® Software

The acoustic problem can be described by the basic governing equations of fluid dynamics in their linearized form. This includes linearized Navier Stokes equations, Linearized Euler equations or Helmholtz equations. The formula for linearized Euler equations is shown below.

$$\frac{\partial \rho}{\partial t} + \rho_0 \, div \, \vec{v'} = 0$$

$$\rho_0 \frac{\partial \vec{v'}}{\partial t} = -grad \, p'$$

Helmholtz equations are limited to low mean flow Mach numbers and, hence, of less interest for the given set-up.

As the problem constitutes an Eigenvalue problem, an Eigenvalue solver would be desired. However, in the presence of mean flow, eigenvalue problems are hard to solve. Therefore, an acoustic source is placed in the domain and its frequency is swept over the range of interest.
The maxima of the amplitudes of the acoustic response in the domain indicate the presence of eigenmodes, then.

In the following, different test cases have been defined to approach the final configuration in a stepwise approach.

2.1 Simple Duct test case

This test case serves as basic validation for the acoustic capabilities of COMSOL Multiphysics.
The configuration has been chosen such that analytical solutions are known. Therefore, a validation both of the set-up procedure and the solver are possible.
The domain has a length of 1.5m and a width of 0.5 m and is filled with ambient air.

The settings were the following:
Physics module:

- *Linear Euler, Frequency Domain*

Background mean flow velocity:

- M = 0 and M = 0.2 (in longitudinal direction)

Boundary Conditions:

- Channel walls: *Rigid wall*
- Channel inlet and outlet: *Pressure* (= 0)

Acoustic source:

- Domain Source

Mesh:

- Quadrilateral mapped mesh
- Max. element length: 0.025m

Study:

- *Frequency Domain*
- Direct solver: MUMPS

The frequencies for the resulting eigenmodes correspond well to the analytically predicted ones (see Table 1). A sample eigenmode is shown in Figure 10.

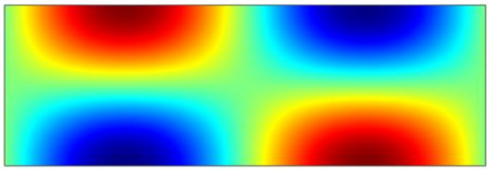

Figure 4. Second order eigenmode of a 2D duct geometry

Table 1. Analytical and numerical eigenfrequencies of the duct case

Eigen mode	Analytic solution		COMSOL (Step: 0.25Hz)	
Mach	0	0.2	0	0.2
L1	114.3	109.8	114.3	109.8
L2	228.7	219.5	228.8	219.5
L3	343.0	329.3	343.3	329.5
T1L1	361.6		361.8	353.5
T1L2	412.2		412.5	401.5

2.2 Rocket Combustion chamber

The geometry of a usual rocket combustion chamber is fairly simple. It is of a basically cylindrical shape which then contracts with a radius and a counter-radius into a nozzle where the fluid is accelerated to supersonic velocities. As the acoustics in the supersonic part are lost due to convection, this part is not further modeled.

Figure 5 shows such typical configuration. The injector head would be attached to the left.

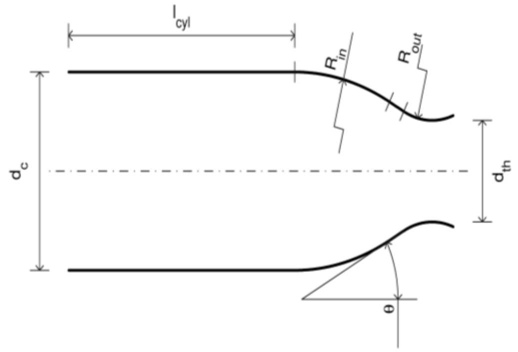

Figure 5. Sketch of a typical rocket combustion chamber

The propellants enter the combustion chamber through a usually flat faceplate of the injector head. In some configurations, the faceplate is equipped with a separation wall pattern – so called baffles – to improve combustion stability.

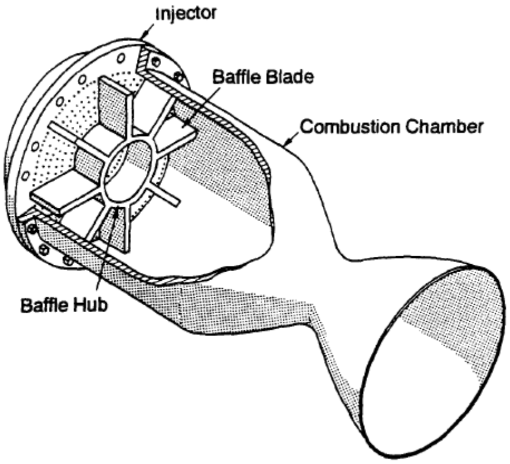

Figure 6. Sketch of a rocket combustion chamber with injector and baffles (Source: [5])

The mean flow in a typical combustion chamber is highlighted in Figure 7. The Mach number reaches 1 in the throat, i.e. the narrowest cross section.

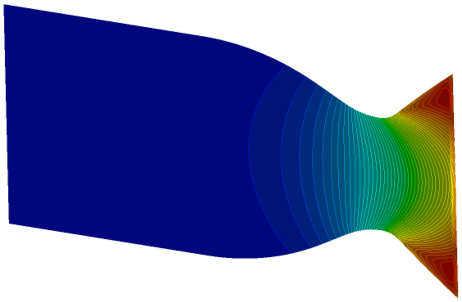

Figure 7. Mach number of the mean flow field calculated with CFX. Ma=1 in the throat

The first step for the calculation was to simulate the acoustics in a quiescent mean flow field on the real geometry of the combustion chamber. The gas was chosen such that is has the uniform properties of the hot, burnt gas but with no mean flow velocity, or gradients.

The utilized mesh is a triangular swept mesh as shown in Figure 8. The domain has been truncated just before the nozzle throat. This ensures subsonic conditions in the domain.

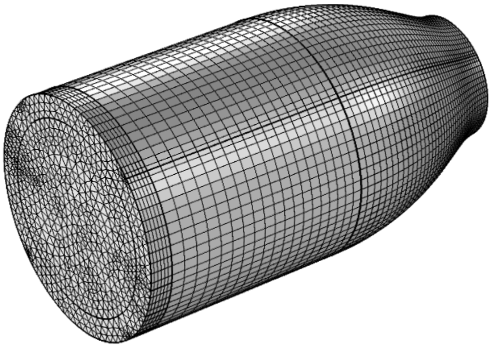

Figure 8. Mesh for the COMSOL acoustic calculations

Settings for the given set-up are:

In the physics module: *Linear Euler, Frequency Domain*

The gas inside the combustion chamber was assumed to be an ideal gas.

The Boundary Conditions are:

- Chamber wall and inlet: *Rigid wall*
- Chamber outlet: *Asymptotic far-field radiation + Outflow boundary*

The acoustic source is a pressure rate of change source modeled as a Gauss point source.

The second step was using the mean flow field from Figure 7 and, hence imposing velocity gradients and high Mach numbers to the acoustic problem.

The three-dimensional mean flow field was imported from CFD via the interpolation function in the component's definition section using default properties.

Figure 9 shows the result of a frequency sweep over a range of frequencies, where different eigenfrequencies are located.

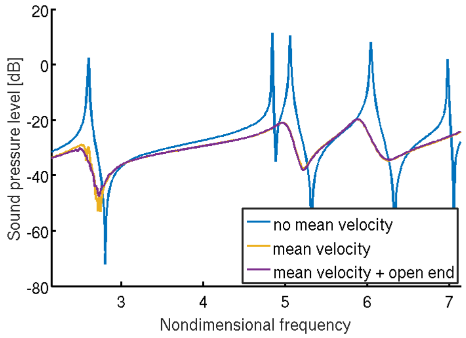

Figure 9. Sound pressure level over non-dimensional frequency for quiescent and physical mean flow field showing the eigenfrequencies as maxima

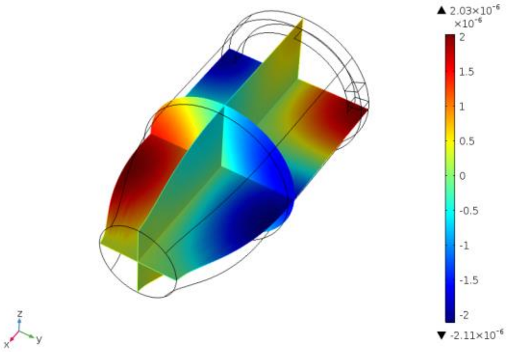

Figure 10. L1T1 Eigenmode of the examined rocket combustion chamber

A shift of the eigenfrequencies to lower values in the case of physical mean flow is visible. This is a usual behavior in the presence of mean flow. Additionally, the maxima appear more damped, which also can be attributed to the flow field. Interestingly, different types of boundary conditions on the outlet do not have a significant effect on the eigenfrequencies. This implies that the convective effects are already dominating the behavior and that the nozzle acoustics are captured reasonably well.

3. Conclusions

The acoustic capabilities of COMSOL Multiphysics have been evaluated using different test cases. First, an analytically known test case has been calculated in order to validate the proper application. In a second step the solver has been applied to a standard rocket combustion chamber in order to assess its acoustic eigenmodes. These have been successfully calculated and appear to be physically correct.

4. References

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