



## Control of cavity acoustics by surface waviness in landing configurations

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#### ABSTRACT

Aircraft noise is dominant for residents near airports when planes fly at low altitudes such as during departure and landing. Flaps, wings, landing gear contribute significantly to the total sound emission. This paper investigates the use of a sinusoidal surface modification application upstream of a cavity as a passive acoustics control device in approach conditions. Optimum sinusoidal amplitude and frequency were previously determined by the means of a two-dimensional computational fluid dynamics analysis for a cavity with a length to depth ratio of 4. The overall sound pressure level was reduced with the surface modification at the majority of the points investigated.

KEYWORDS : Aeroacoutics, Landing Configurations, Cavity Noise, Surface waviness, OpenFOAM.

#### NOMENCLATURE

- D Cavity Depth
- L Cavity Length
- δ Boundary layer thickness
- *f* Acoustic frequency of disturbance
- $f_m$  Frequency of the m<sup>th</sup> mode
- p'- Pressure perturbations
- $p_{rms}$  Root mean square pressure
- $R_e$  Reynolds number

St - Strouhal number

#### **1** INTRODUCTION

 $P_{ref} - P_{ref} = 2 \times 10^{-5}$  Pa, The value adopted as the minimum audible sound pressure variation SPL - Sound Pressure Level PSD - Power Spectral Density OASPL - Overall Sound Pressure Level *fft* - Fast Fourier Transform OpenFOAM - Open Field Operation And Manipulation

Airframe noise refers to the noise generated by all components of the aircraft except the propulsion system. With the implementation of quieter jet propulsion systems, airframe noise becomes especially significant for larger, modern commercial aircraft. Moreover, the environmental regulations are concerned with the noise levels at and around airports during the take-off and landing situations. The international civil aviation organization (ICAO) annex 16 is the one involved with setting the standards of noise levels for aircraft and engine manufacturers. Thus, the radiation of airframe noise will be a necessary component of the development of future commercial aircraft, particularly in the subsonic fleet. Earlier investigations indicated that there are many sources that contribute to airframe noise. One such component is cavity noise. Flow over cavities on solid surfaces became a topic of interest in the late 1950s and early 1960s with the introduction of high speed combat aircraft. The primary concerns at that time were the buffeting of the cockpits and the drag induced by flow over bomb bays and landing gear compartments, Fig. 1. In many experimental studies, it has been observed that cavity flow produces intense acoustic tones.



Figure 1: Bomb bays and landing gear.

#### 2 CONTROL OF CAVITY NOISE

Many control techniques have been tested in order to reduce the cavity acoustic tones with variable results. Both active and passive control systems have been used. Passive control devices are the easiest to implement and a wide variety of systems were tested, in particular: spoilers, mass injection and modification of the cavity leading and/or trailing edge. These concepts sometimes proved to be very effective in reducing energetic tones but, in general, they did not succeed in suppressing multiple acoustic modes simultaneously.

The effect of a waviness surface in incompressible cross flow parallel to the leading edge of the cavity is another passive device that proved to be very efficient, as shown first by GARRY Hughes and Laurent DALA [1].

#### 3 INVESTIGATION OF FLOW PHENOMENA FOR CAVITY FLOW

#### 3.1 Cavity geometry

Fig. 2-(a) illustrates the length L, depth D and width W with the stream wise flow direction and the Fig. 2-(b) carries details showing the incoming boundary layer at the leading edge of the cavity, shear layer over the cavity and the pressure perturbation from the trailing edge of the cavity due to the impingement of the shear layer on the corner of the downstream of the cavity. Cavities can be classified based on the geometrical rations of the length to depth (L/D).



Figure 2: Cavity dimensions and flow characteristics

### 3.2 Ratio of Length over Depth L/D

Cavity flows exhibit a wide variety of phenomena whose precise nature depends sensitively on a number of parameters including the value of L/D. In the literature, vastly different values of L/D have been quoted to define the flow types. For instance: L/D < 7 for open and L/D > 13 for closed cavity flow is reported by Stallings and Wilcox [2] whereas L/D < 10 for open and L/D > 13 for closed cavity flow is reported in the work of Plentovich [3]. Similarly, Dix and Bauer [4] quote L/D < 9 for open and L/D > 13 for closed cavity flow whereas Srinivisan and Baysal [5] quote L/D < 3 for open and L/D > 10 for closed cavity flow fields. Tracy and Plentovich [6] investigated the variations in the values of L/D and concluded that the vast disagreements in the literature were due to the dependence of the cavity flow type on Mach number as well as L/D. Fig. 3-(b) shows separation point at the upstream of the cavity with dividing streamline for the open





Open cavities refer to flow over cavities where the boundary layer separates at the upstream corner and reattaches near the downstream corner. Open cavities may further be divided into shallow and deep cavities. The cavities with aspect ratio L/D > 1 may considered as shallow and L/D < 1 for the cavities may be considered deep Fig. 3-(a). Cavities are closed when the separated layer reattaches at the bottom of the cavity and again separates ahead of the downstream wall of the cavity.



#### Figure 3: Schematic of deep (a), and shallow cavities: open (b), and closed (c)

#### 3.3 Incoming flow

The influence of the free stream flow velocity has been investigated in the majority of the experimental studies. The cavity flow physics and its resonance depend on several flow parameters.

#### 3.3.1 Mach number

The effects of Mach number on non-dimensional frequency  $fb/U_e$  have been studied by many investigations for both laminar and turbulent boundary layers. On the basis of high speed shadow-graphs of cavity oscillation, Rossiter [9] speculated that periodic vortices are shed at the upstream corner in sympathy with the pressure oscillation produced by interaction of the vortices with the downstream corner. Based on this idea Rossiter derived a formula for the oscillation frequency. Heller [10] and Covert studied shallow cavities over a wide range of Mach numbers and correlated a great many experimental results with Rossiter's formulation of cavity oscillation frequency, the vortices shed from the upstream cavity corner are assumed to convect at a constant phase velocity through the shear layer, resulting in a linear phase distribution. The variation in the resonant frequencies with Mach number is consistent with the Rossiter Eq. 1.

#### 3.3.2 Boundary layer thickness

The boundary layer thickness at the cavity lip is also an important parameter [7]. Colonius [11] states that the momentum thickness  $\theta_0$  at the leading edge of the cavity plays a vital role in the selection of the modes and in governing the growth of the shear layer. They also found  $L/\theta$  for lower limit for the cavity resonance to be approximately  $L/\theta \approx 80$ . When the ratio of the cavity length to the momentum thickness of the incoming boundary layer ( $L/\theta$ ) is in the range  $80 < L/\theta < 120$ , the self-sustained oscillations take place in the shear layer mode. When  $L/\theta$  exceeds 120, another mode of cavity oscillation has been observed, but has received much less attention, and is relatively poorly understood. In incompressible experiments for an axisymmetric cavity, Gharib and Roshko [12] observed a wake mode, where the oscillating flow over the cavity resembles the wake behind a bluff body, rather than a free shear layer. Flow features in this wake mode were qualitatively very different from those in the shear-layer mode described by Rossiter, and wake mode was accompanied by a large increase in drag. Similar dramatic increases in drag had been previously observed by Fox [13] as the cavity length was increased, in flows with thin laminar upstream boundary layers, and Roshko [14] observed an intermittency analogous to the large fluctuations of drag which occur on a bluff cylinder in the critical range of





Reynolds number, where the flow may be switching between shear-layer mode and a type of wake mode.

Sarohia [8] stated that the parameters cavity depth D and initial momentum thickness  $\theta_0$  at the leading edge also are as important as the cavity length L, for a fixed value of the edge velocity  $U_e$ , depth D and Width W, there exists a maximum value of shear thickness above which the cavity does not oscillate. As the shear layer thickness  $\delta_0$  is decreased ( $\delta_0 < \delta_{0_{max}}$ ), the frequency of cavity oscillations increases.

#### 3.4 Flow Models

**Rossiter** In 1964 [9], proposed a semi-empirical formula for predicting the discrete tones detected in the experiments. The vortices which are shed from the cavity leading edge are convected downstream until they interact with the aft cavity wall, generating acoustic pulses. These acoustic pulses propagate upstream in the cavity eventually reaching the front cavity wall. At this time they induce separation of the shear layer which results in the shedding of another vortex, completing the feedback loop. Based on this description a formula was proposed to predict the frequencies, given by Eq. 1:

$$f_m = \frac{U_\infty}{L} \frac{m - \gamma}{M_\infty + \frac{1}{\kappa}} \tag{1}$$

Where m is an integer index for the frequency of interest (m=1, 2, 3...), is constant for a fixed L/D and  $\kappa$  represents the ratio of the speed of the vortices to the free-stream speed.

The Fig.4 illustrate typical spectra for cavity with open flow as well as a section of the resonant range classification presented in [15] corresponding to the cavity dimensions of interest for this study. Where  $\kappa$  is empirical constant,  $\kappa = 0.57$  yields a fairly good collapse with the experimental data. For shallower cavities (L/D from 4 to 10), Rossiter adjusted the constant, by using the values of Table.1.

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Modes [15]

#### Table 1: Values of $\gamma$ as a function of the length-to-depth ratio L/D, from Rossiter [9] L/D $\gamma$ 130 4 0.256 0.38 0.54 110 8 1000 Frequency, Hz 1500 10 0.58 Figure 4: Typical Spectral View of Rossitor

**Bilanin and Covert's** In 1973 [16], this analysis consists of three parts: the analysis of the shear layer stability: the calculation of the interior acoustics of a rectangular cavity; and the prediction of the cavity oscillation frequency. In the first part of the calculation, the shear layer is modeled as a vortex sheet that is only dependent upon the depth of the cavity. With this assumption, the effect of shear layer impingement at the downstream edge of the cavity is eliminated, and the separation of upstream and downstream edge effects and the pressure field from the upstream edge have little effect on the vortex sheet except near the upstream edge.

Therefore, the only boundary conditions required in the stability analysis are the rigid wall boundary condition at the floor of the cavity, the kinematic and dynamic boundary conditions at the shear layer interface, and the outgoing radiation boundary condition above the shear layer. According to the photographs taken by Krishnamurty [17], the shear layer impingement generates an acoustic source at the downstream edge of the cavity. Hence, in the second part of the analysis, Bilanin and Covert [16] assumed a mass addition and removal at the downstream edge of the cavity as the cause of the acoustic source. The following expression is derived:

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(2)

$$St = \frac{n - \frac{3}{8} - \frac{\phi}{2\pi}}{\frac{\alpha_r U_{\infty}}{\omega} + M \frac{c_+}{c}}$$

Where  $\phi$  and  $2\pi \times 3/8$  correspond to the phase lags, respectively due to the upstream and downstream edges,  $\omega$  and  $\alpha_r$  are the radian frequency and the real part of the complex wavenumber of the unstable vortex sheet solution respectively and  $U_{\infty}$  is the velocity outside the cavity. This formula takes the compressibility factor into account through the ratio  $c_+/c_-$  between the exterior and interior sound speeds.



Figure 5: Classes of possible of vortex-corner interactions. From Rockwell and Knisely [18]

In the study by Bilanin and Covert [16], the internal cavity wave structure is uncoupled from the shear layer motion in order to simplify the analysis. It is assumed that the cavity internal pressure modes force the shear layer only at the upstream edge and, therefore, only the downstream wave motion of the shear layer is considered. To eliminate this assumption, Heller and Bliss [10, 19] introduced the concept of the pseudopiston effect Fig. 5 [18]. This is similar to the replacement of the downstream cavity wall with an oscillating piston. The mass addition and removal creates pressure fluctuations that travel upstream in the cavity, and further amplifies the vortices shed at the upstream edge. In this manner, the internal cavity acoustic wave is coupled with the shear layer motion, and the feedback loop is complete.

#### 4 COMPUTATIONAL AERO-ACOUSTICS

Aeroacoustics is a study of flow-induced noise, concerned with the sound generated by turbulent and/or unsteady vortical flows including the effects of any solid boundaries in the flow. With the increases in performance of computers, the numerical simulation of aeroacoustics, or computational aeroacoustic (CAA), has become more popular. Computational Aeroacoustics combines the classical approaches of flow field computation with acoustics. Computational methods for flow-generated sound can be divided into two kinds: direct computation and indirect, or hybrid computation.

- The direct approach computes the sound together with its fluid dynamic source field by solving the governing equations without modeling;
- In the hybrid approach, the computation of flow is decoupled from the computation of sound, which can be performed during a post-processing stage based on aeroacoustic analogy.

#### 5 ACOUSTIC ANALOGIES

Modern aeroacoustic science was pioneered in the 1950's by Sir James Lighthill [20] who derived an 'acoustic analogy' for the estimation of the intensity of sound radiated by a turbulent flow. Lighthill transformed the Navier-Stokes and continuity equations to form an exact, inhomogeneous wave equation whose source terms are important only within the turbulent region.





#### 5.1 Lighthill's acoustic analogy

Lighthill gives a reformulation of the fluid dynamics equations in such a way that he obtains a wave equation for the acoustic density fluctuations with a source term on the right hand side. The following equation is obtained:

$$\frac{\partial^2 \rho}{\partial t^2} - C_0^2 \Delta \rho = -\frac{\partial^2 T_{ij}}{\partial X_i \partial X_j}$$

(3)

Where  $\rho$  is the density,  $C_0$  is the ambient sound speed and  $T_{ij} = \rho u_i u_j + (P - c_0^2 \rho) \delta_{ij} - \tau_{ij}$  is known as the Lighthill stress tensor,  $u_i$  p,  $\tau_{ij}$  being the velocity components, the pressure and the viscous stresses respectively.

#### 5.2 Curle's Analogy: the influence of solid boundaries

As an extension to Lighthill's acoustic analogy, Curle [21] proposed a formal solution to Lighthill's analogy in 1955 to include the influence of the solid static boundaries. The presence of surfaces strongly modify the sound production:

- Changes in the radiated acoustic field in comparison with the previous case of free turbulent flows;
- Extension of the integral formulation to the case of wall-bounded turbulent flows;

We assume a solid body, placed normally to a mean flow: The volume V is the entire space occupied by the fluid, and V is delimited by a surface S enclosing the body.  $\vec{n}$  is the outer normal to the volume V at the surface S, directed towards the body.

$$\rho(\vec{x},t) = \frac{x_i x_j}{4\pi c_0^4 |\vec{x}|^3} \frac{\partial^2}{\partial t^2} \int \int_V \int [T_{ij}] d\vec{y} - \iint_S \frac{1}{4\pi c_0^2 |\vec{x}|} \frac{\partial}{\partial t} [\rho u_i] n_i dS - \frac{x_j}{4\pi c_0^3 |\vec{x}|^2} \frac{\partial}{\partial t} \iint_S [\rho u_i u_j + p\delta_{ij} - \tau_{ij}] n_i ds \quad (4)$$

- The first integral (volumic integral) represents the noise due to the turbulence in the source volume, similarly to the case of a free turbulent flow;
- The second integral (surfacic integral) results from a volume injection through the surface S
  enclosing the body, which can be due to a flow through a porous surface or to pulsations of
  the body;
- The third integral (surfacic integral) results from the momentum flux through the surface S and from the surface stresses on S (pressure and viscosity forces);

#### 6 DOMAIN GENERATION METHODOLOGY

The geometrical parameters of the cavity model in paper are displayed in Fig. 6 (a- baseline Cavity geometry and b- wavy cavity geometry). The computational domain and boundary conditions shown in Fig. 7 are taken from the computational domain of Garry Hughes and Laurent Dala [1], the sound signals are received on receiver-A. Different surface modifications were simulated by varying the amplitude and frequency of surface waviness was constructed using **OpenFOAM** program.



#### Figure 6: Cavity geometry

All simulations were performed on the cavity of aspect ratio L/D = 4. Through out the work, the length of the cavity is maintained as 50.8 mm and depth of the cavity as 12.7 mm. Fig. 7 illustrates





the schematic diagram of two dimensional domain adopted to simulate cavity flows. The flow is from left to right hand side. The domain extends between  $0 \le x \ /D \le 45$  and  $-1 \le y \ \backslashD \le 8$ .

The computational domain extends to 20D and 20D upstream and downstream of the cavity leading and trailing edges, respectively.



Figure 7: Schematic diagram of the computational domain

Table 2: Details of the Geometry		
Total length of the domain	558.8 mm	
Height of the domain	101.6 mm	
Cavity length L	50.8 mm	
Cavity depth D	12.7 mm	
Aspect ratio of the cavity $\frac{L}{D}$	4	

The Table 2 summaries the details related to the geometry of the two dimensional cavity. Fig. 8 shows the density of mesh resolution near the walls and in the cavity region. The boxed region which is highlighted at the upper left corner represents the high mesh density. It is the region where the shear layer and other important mechanisms begin for hydrodynamics and aeroacoustics.



Figure 8: Mesh density: a) Baseline cavity b) Wavy cavity

#### 7 RESULTS

#### 7.1 Aerodynamics

When a shear layer passes a cavity, it mainly keeps flowing downstream but the rest comes into the cavity and forms a recirculating flows. The predictions of instantaneous velocity flow field from **LES** simulations are shown in Fig. 9.





b) Wavy cavity with Ampl. 3.25 Cyc. 3

Figure 9: Instantaneous flow field from LES simulations

#### 7.2 Shear mode

The test case (Ampl. 0 Cyc. 0) oscillates in shear mode. Fig.10 illustrates instantaneous vorticity contours in the cavity flow-field at different flow time after 60 computational periods.

The turbulent boundary layer which separates from the leading edge of cavity forms an oscillating shear layer. Fig. 10-(a) shows the shear layer stretching from the upstream of the cavity and is parallel to the bottom of the cavity. Over the right upper corner of the cavity, shear layer with a tongue like structure extends to the downstream of the cavity from the vortex near to the vertical





wall of the cavity. Fig. 10-(b) describes the complex interaction between the shear layer and the vortex at the downstream wall of the cavity. The incoming shear layer extends until the middle of the cavity region and the lip of the shear layer swipes on the vertical wall at the trailing edge of the cavity. (The swiping action cuts the tongue like shear layer to travel downstream of the cavity.)

The shear layer which extends due to the oscillation, impinges on the upper right corner of cavity and breaks into two (see Fig. 10-(c)) and at time period 3T/4 i.e in the Fig. 10-(d), one part of the lip of the broken shear layer enters the cavity creating a eddy close to the downstream wall with the size of cavity depth, while the other part of the shear layer moves downstream of the cavity with less energetic eddies.



Figure 10: Instantaneous vorticity contours in the baseline cavity. (a) 60.25T; (b) 60.5T; (c) 60.75T (d) 70T

#### 7.3 Wake mode

Fig. 11 shows the instantaneous vorticity fields U over a period. A vortex is formed from the trailing edge and fills the cavity region is shown in Fig. 11-(a). In Fig. 11-(b), the vortex detaches and impinges on the downstream corner of the cavity. Due to the impingement, is ruptured and moves out of the cavity, while another eddy enter the cavity from the leading edge of the cavity (see Fig. 11-(c)). The eddy which is broken at this point of time moves downstream of the cavity, while another new eddy grows to fill the cavity is shown in the Fig. 11-(d). The flow above the cavity region is affected by the flow from the cavity.



Figure 11: Instantaneous vorticity fields U for wake mode at four different times (a-d) corresponding to approximately a quarter of a period of oscillations. Only a small portion of the computational domain near the cavity is shown

### 8 AEROACOUSTIC

**Acoustic Parameters:** The pressure perturbations  $p'(p' = p - p_0)$  which propagate as waves and which can be detected by the human ear. For harmonic pressure fluctuations the audio range is  $20Hz \le f \le 20kHz$  The Sound Pressure Level (SPL) is a logarithmic scale measure of the pressure





unsteadiness in which the minimum pressure fluctuation detected by the human ear  $p_{ref} = 2 \times 10^{-5} Pa$  is taken as the reference. For continuous pressure signals, the SPL is defined by:

$$SPL = 10\log(\frac{PSD}{p_{ref}})$$
(5)

The PSD describes how the power of a signal or time series, in our case the time dependent pressure, is distributed with frequency. The PSD spectrum is determined by means of a Fast Fourier Transform (FFT) utilizing windowing as to smoothen the PSD estimate, in our case the Hanning window. The

FFT of a signal P(t) is defined as  $FFT(t, f) = \int_{-\infty}^{\infty} P(\tau) w(\tau - t) e^{-j2\pi f\tau} d\tau$  where w(t) is the Hanning

window function, applied to obtain a clear definition of the fundamental frequencies. Time averaging the pressure fluctuations one would obtain the mean pressure  $\overline{P} = \frac{1}{N-N_0} \sum_{k=N}^{N} P_k(t)$  where N is the

total number of samples taken and N<sub>0</sub> is the first sample number at which the time averaging starts. The root mean square pressure is therefore calculated via the equation  $P_{rms} = \frac{1}{N-N_0} \sum_{k=N_0}^{N} \left(P_k(t) - \overline{P}\right)^2$ 

Using the acoustic spectrum results, an overall sound pressure level (OASPL) can be obtained by adding all noise amplitudes of the spectrum, the OASPL can be obtained applying the following expression:  $OASPL = 20 log \sqrt{\sum_{i} (10^{SPL_i/20})^2}$ 

Sound pressure levels (SPL) for the acoustic field above the cavity predicted by Rowley, et al [22] and paper are shown in Fig. 12, peak radiation to the far field occurs at an angle of about 135<sup>0</sup> from the downstream axis.



Figure 12: SPL distributions. (a) 2D-DNS predicted by Rowley, et al. [22]; (b) 2D-LES with surface wavy

Fig. 13 shows the sound pressure level of the computed acoustic signal at Mach 0.3 (flow velocity 99.44 m/s). The spectral resolution of these results is 6.97 Hz. over the whole frequency range [0-10000] Hz. From the acoustic analysis it can be seen that the significant peak of the sound pressure level is at the frequency 2000 Hz correspond to the  $2^{nd}$  Rossiter mode.



Figure 13: SPL at one receiver for baseline cavity

# Table 3: Rossiter modal frequencies Wth associated Strouhal Numbers [9]

m	St	f(Hz)
1	0.412	807.60
2	0.962	1884.39
3	1.512	2961.19
4	2.068	4037.98
5	2.612	5114.78
6	3.163	6191.57
7	3.713	7268.37
8	4.263	8345.16
9	4.813	9421.96
10	5 363	10498.75





The highest sound pressure level at this frequency is 129 dB (for receiver A, Fig. 7). the peaks at 840 Hz, 2000 Hz, 4080 Hz, 6122 Hz, 80150 HZ and 10300 HZ correspond very well to the results predicted by Rossiter, Eq. 1. (see Table 3)

It is seen that in Fig. 14-(a) the cavity for an applied surface waviness with frequency of  $19.7 \times 10^{-3}$  and  $11.8 \times 10^{-3}$  cycles per mm increase the resonance peak by 9 dB compared to the baseline case and also the peak of the sound pressure level is at the frequency 1000 Hz correspond to the  $1^{st}$  Rossiter mode for wake mode.





Fig. 15 shows frequencies of the two most energetic peaks in the spectra for the series of run with L/D = 4, compared to experimental data and predictions from Eq. 1, the transition to wake mode oscillations for M > 0.3.



Figure 15: Strouhal numbers for peaks in spectra for the shear-layer mode and wake modes

The results for surface wavy control, Fig. 14-(b), show a considerable attenuation of the dominant Rossiter peak, it was clarified that the tonal sound reduced for frequency of  $4.92 \times 10^{-3}$ ,  $9.84 \times 10^{-3}$  cycles per mm. The maximum noise level of 116 dB was observed at f= 625 Hz for frequency  $4.92 \times 10^{-3}$  cycles per mm and the maximum noise level of 127.8 dB was observed at f = 1095 Hz for frequency  $9.84 \times 10^{-3}$  cycles per mm. It was observed that the attenuation achieved using this configuration was of the highest value, giving an overall reduction in SPL of 14 dB. The comparison of the numerical simulation with the experimental measurements for acoustic part has not been carried out yet. But this study proves the influence of the surface wavy in the attenuation or amplification of sound and its intensity.

### 9 CONCLUSION

A complete two-dimensional analysis of both the baseline and the modified configuration were carried out. Additionally the flow regime was demonstrated with success by the use of CFD flow visualisation. The results of different geometry modifications applied to the leading edge of a cavity with length to depth ratio of 4, in order to reduce the resonance of flow at Mach 0.3 have been presented. The





amplitude of 3.25 mm and the frequency of  $4.92 \times 10^{-3}$  cycles per mm was observed as achieving the best reduction in cavity resonance.

To fully understand the wavy surface impact on the cavity flow control, the following further work is required:

- Applying the used control mechanism on a range of Mach numbers is needed to further verify the effectiveness of the control system;
- Increasing the mesh density and study the influence on accuracy of the results;
- Wind Tunnel testing of an optimum 2D model.

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