14th International Symposium on Turbulence and Shear Flow Phenomena (TSFP14)
Heidelberg, Germany, July 28-31, 2026

K-ω SST BASED HYBRID RANS/LES SIMULATION FOR SUPERSONIC AND HYPERSONIC FLOWS

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ABSTRACT

The accurate prediction of turbulent flows in supersonic and hypersonic regimes remains a challenge in computational fluid dynamics due to their complexity. While Reynolds Averaged Navier–Stokes (RANS) methods are computationally efficient, they struggle to capture the unsteadiness of massively separated turbulent wakes. Hybrid RANS/LES (HRL) methods strike a promising balance, leveraging RANS's near-wall robustness and LES's capability to capture large-scale structures.

This study investigates the application of HRL methods to a supersonic cylindrical afterbody flow using experimental data from Herrin and Dutton (1994) as a reference. A modified hybrid approach is examined, including a method tailored for supersonic and hypersonic flows. The goal is to assess its ability to capture key flow features such as separation, wake development, and unsteady behavior.

The Zonal Detached Eddy Simulation (ZDES) method by Deck and Renard (2020) is selected for its flexibility and accuracy in separated flow simulation. A new inhibition function is introduced to better handle supersonic and hypersonic separated flows based on an expansion fan sensor.

Results show that the HRL method improves the prediction of the recirculating region length and captures unsteady flow features better than RANS. Spectral Proper Orthogonal Decomposition (SPOD) analysis identifies three dominant modes associated with global flow behavior, shedding mechanisms, and shear layer instabilities, validating the method's ability to resolve unsteady flow dynamics.

This work serves as a preliminary step toward applying hybrid methods in the hypersonic regime, demonstrating their potential for improving the prediction of complex turbulent flows.

INTRODUCTION

The accurate prediction and understanding of turbulent flows in supersonic and hypersonic regimes remain a central challenge in computational fluid dynamics. These flows are inherently complex due to strong compressibility effects, shock-boundary layer interactions, and high thermal gradients.

The simulation of such flows typically relies on Reynolds-Averaged Navier–Stokes (RANS) methods owing to their computational efficiency. However, RANS models struggle to reproduce the fine-scale unsteadiness of massively separated turbulent wakes, especially in high Mach number regimes.

Recent work by Raje et al. (2025) underscores the challenges faced by RANS modeling in hypersonic turbulence. They highlight key multi-physics factors for which the predictive capability of conventional RANS formulations is severely limited.

To overcome these limitations, there is an interest in the use of hybrid RANS/LES (HRL) approaches, which combine RANS near-wall robustness with LES's ability to resolve large-scale structures in separated and wake regions. These methods offer a promising compromise between fidelity and computational cost, particularly for complex geometries and high-Reynolds-number supersonic and hypersonic flows.

In the following, we investigate the application of HRL methods to the case of a supersonic cylindrical afterbody flow, using the experimental data of Herrin and Dutton (1994) as a reference. A modified hybrid approach is introduced especially for supersonic and hypersonic flows. The goal is to assess its ability to capture key flow features, such as separation, wake development, and unsteady behavior that remain inadequately predicted by conventional RANS models. This work serves as a preliminary step toward the application of hybrid methods in the hypersonic regime.

HYBRID RANS/LES METHODS FOR SUPERSONIC AND HYPERSONIC FLOWS

Numerous HRL approaches have been studied for aerodynamic cases, from the DES introduced by Spalart et al. (1997) to the more recent CES developed by Heinz and Fagbade (2024). For the current study, the Zonal Detached Eddy Simulation from Deck and Renard (2020) has been selected due to its flexibility of use, the handling of the grey area (switch zone between RANS and LES) and its accuracy in separated flow simulation. The recent extension for k-ω SST by Renard et al. (2024) for the type II ZDES seems to be a suitable candidate to simulate a cylinder afterbody flow.

Use of k-ω SST ZDES II

Contrary to Spalart-Allmaras based HRL with the wall distance, the RANS turbulent characteristic length is not directly used in the equations. It is defined as $L_{RANS} = \sqrt{k}/\beta^{*}\omega$. In the case of a LES area, this turbulent length is switched to the LES one $L_{LES} = C_{DES}\Delta^{II}$, where C_{DES} is a model constant and Δ^{II} the cell size computed as a combination of Δ_{max} and the vorticity length scale Δ_{ω}. The dissipation term of the k equation is then replaced by $\rho k^{3/2}/L_t$ where L_t is either L_{RANS} or L_{LES}. When the switch to LES is made, the subgrid scale model corresponds to a transport equation of k.

Considering the case of a separated flow, Renard et al. (2020) introduced new shield functions to protect the boundary layer completely in RANS upstream of the separation point and in LES downstream. Nonetheless, they noticed that an inhibition function is required to annihilate the boundary layer protection at the separation point to ensure the LES use in this area. The latter is computed using a vorticity gradient to identify the shear layer.

In the present work, the authors have chosen to ignore the reconstruction of the turbulent viscosity ν_t^R and the vorticity magnitude Ω_{bis}, introduced by Renard et al. (2024), since the irregularity effects of mesh refinement on the SST turbulent profile are not observed in the studied configuration.

Shielding function for supersonics/hypersonics

Another inhibition function is introduced in the present work emphasizing supersonic and hypersonic separated flows. In such cases, near the separation point, an expansion fan is involved and could be used to trigger the inhibition function. Thus, an expansion fan sensor is proposed, inspired by the work of Sciacovelli et al. (2021) on a shock sensor. It combines a Ducros sensor:

$$D = \frac{(\boldsymbol{\nabla}.\boldsymbol{U})^2}{(\boldsymbol{\nabla}.\boldsymbol{U})^2 + |\boldsymbol{\omega}|^2} \tag{1}$$

and the Bhagatwala and Lele (2009) one, modified to detect an expansion fan instead of shock:

$$S_f = \frac{1}{2}\left(1 - \tanh\left(2.5 - 10\frac{\delta x}{c}\boldsymbol{\nabla}.\boldsymbol{U}\right)\right) \tag{2}$$

with $\boldsymbol{\omega}$ the vorticity, c the speed of the sound and δx a characteristic length which is set to δ, the boundary layer thickness at the separation point. Then, both sensors are combined, $\varphi_f = D \times S_f$, and the new inhibition function is built:

$$f_R(\varphi_f) = 1 - \tanh(C_1\varphi_f) \tag{3}$$

A valuable advantage of this function, compared to the original one, is that it does not require to compute the vorticity gradient.

CYLINDER AFTERBODY CONFIGURATION

This section aims to investigate supersonic separated flow in RANS/LES and validate the use of the inhibition function based on an expansion fan sensor. To that end, the test case of the cylinder afterbody carried out by Herrin and Dutton (1994) is selected. The $M = 2.46$ and $Re = 52 \times 10^6$ flow has been used in several studies and offers time-averaged and unsteady data for comparison.

For the computation, only the rear part of the cylinder is selected, and an inflow boundary condition is set to match the boundary layer thickness of the experiment at the end edge of the cylinder. Particular attention is paid to the structured mesh generation near the shear layer area and then in all the LES zones. To that end, a 164 million-cell grid is generated to carry out the computation. Second-order Heun scheme is selected for time discretization. Besides, the Koren et al. (1997) slope limiter is used combined with the SLAU numerical scheme to reach third-order in spatial discretization. No forcing method is used since the sharp corner of the geometry is sufficient to trigger turbulence.

Before computing the whole simulation, the effectiveness of the expansion fan sensor proposed in the present work, is checked. The Figure 1 shows the value of the sensor for the current cylindrical afterbody configuration, with the constant c_1 set to 5. The sensor well captures the area corresponding to the expansion fan, immediately after the trailing edge, without any side effects, which validates its definition and implementation.

Results

The Figure 2 underlines the RANS and the LES resolution areas for the current configuration, the switch presented here is time-averaged. The intermediate zones are called grey areas and tend to be minimized. The LES part is pinpointed from the aft region of the cylinder to the output of the wake, which corresponds to the unsteady behavior area of the flow. The

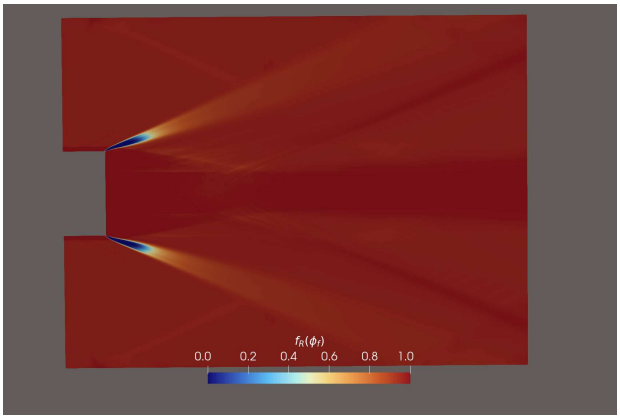

Figure 1. Expansion fan sensor $f_R(\Phi_f)$

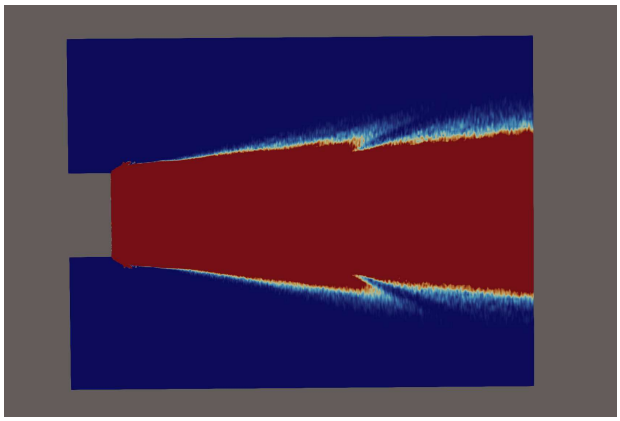

Figure 2. Time-averaged switch between RANS (b) and LES

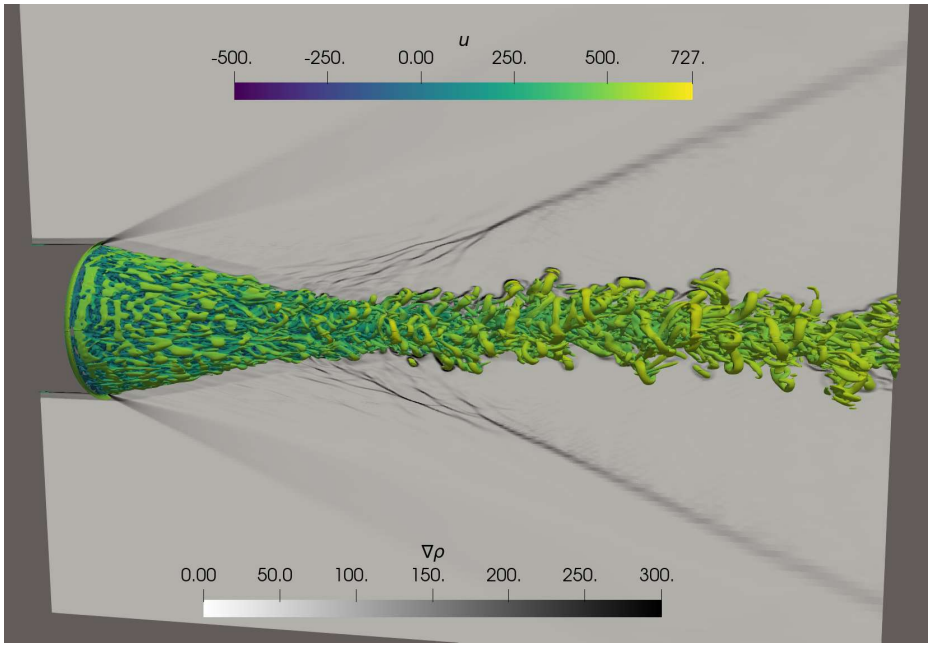

Figure 3. Q-criterion contour colored by the streamwise velocity and density gradient at the mid-plane of the Herrin and Dutton cylinder afterbody flow.

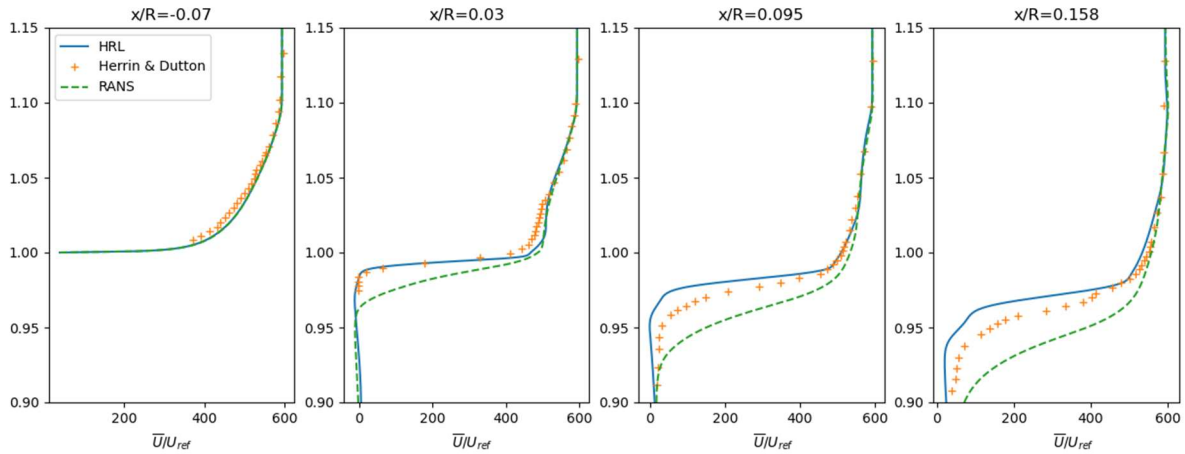

Figure 4. Time-averaged streamwise velocity at four points along the longitudinal axis for the experimental data of Herrin and Dutton (1994), the computational results of the present work in HRL and in RANS.

upstream part is then, as desired, resolved using the RANS approach.

The length of the recirculating region measured in the experiment, $L_R = 0.67R$, is recovered in the present computation, which underlines the improvement of the method compared to RANS simulation where it tends to overestimate its size. The Q-criterium contour shown in Figure 3 underlines the abundance of turbulent structures in the flow obtained with the HRL computation, which cannot be captured by RANS method. The unsteadiness is highlighted in the recompression region regarding the density gradient and, on a smaller scale, inside of the shear layer.

Then, the time-averaged velocity at four positions in the flow direction is shown in Figure 4. As expected, HRL results better fit the experimental data downstream the rear part of the cylinder than the RANS ones. Both methods are identical at the first position since it is located upstream the separation point where the HRL method is switched to the RANS one. Nonetheless, for the last two locations, the velocity profile inside the shear layer is not perfectly recovered.

The major improvement of using a HRL method compared to RANS one is the capture of unsteadiness. Figure 5 depicts the velocity fluctuation at three positions in the recirculating area. The HRL computational results show good agreement with the experimental data at the first location, both in terms of the peak of fluctuation position and its value. For both locations downstream, the position of the fluctuation is correctly captured, although the value is a little overestimated. Again, it corresponds to the shear layer area.

The same observation is made regarding Figure 6 for the maximum value of the time-averaged and azimuthal-averaged velocity fluctuations along the longitudinal axis downstream of the aft of the cylinder. The position of these maxima is located inside the shear layer. The highest values are captured in the second half of the recirculating bubble and collapse right in the recompression region. Thus, the present numerical setup allows

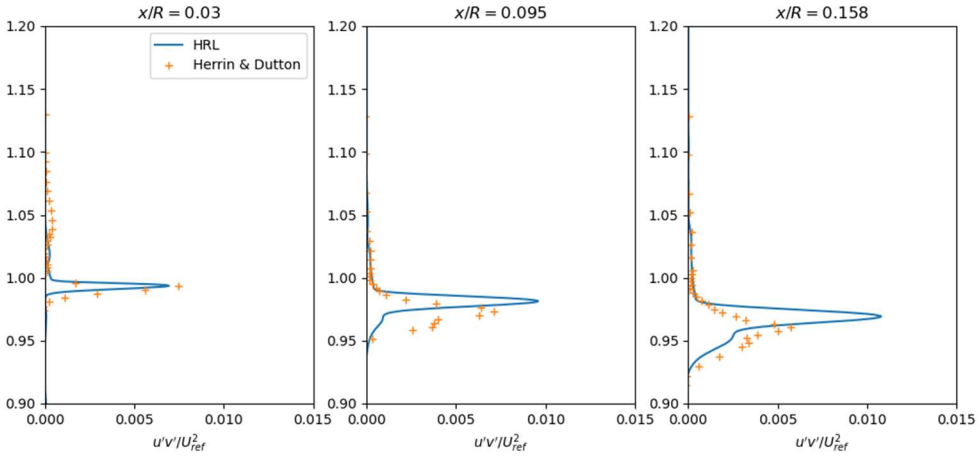

Figure 5. Time-averaged velocity fluctuation at three points along the longitudinal axis for the experimental data of Herrin and Dutton (1994) and the computational results of the present work in HRL.

the development of unsteadiness which corresponds to the experimental observations. The overprediction of the fluctuation could be explained by the SGS model, the statistic convergence or numerical effects and could be investigated in the future.

Spectral analysis

A Spectral Proper Orthogonal Decomposition (SPOD) is then computed based on 800 snapshots, with 400 snapshots per block and an overlap of 50%. This configuration is not optimum but is a good compromise with regard to the available data. The python package PySPOD developed by Mengaldo & Maulik (2021) and Rogowski et al. (2024) is used for this purpose.

The Figure 7 shows the energy spectra pre-multiplied by the frequency. Three main peaks are clearly identified. The first one at low frequency (500 Hz) corresponding to a Strouhal number (St) of 0.05 is identified as a global mode associated with the "breathing" of the recirculation bubble. Simon et al. (2006) underlined an identical frequency for the same configuration and the associated SPOD mode, not shown here, is similar to the one observed by Canova et al. (2024). Thus, despite the limited number of snapshots available, the current simulation recovers the low frequency behavior of the base flow.

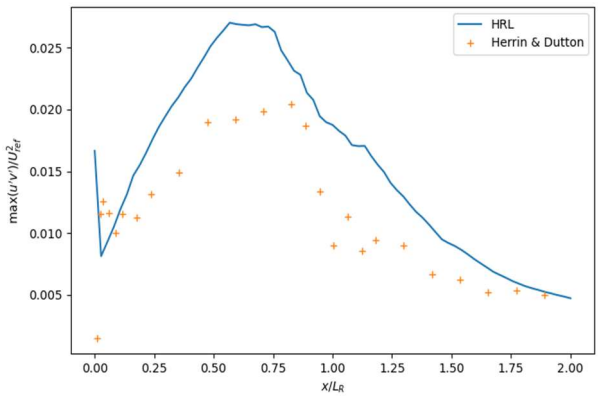

Figure 6. Maximum time- and azimuthal-averaged velocity fluctuation along the longitudinal axis for the experimental data of Herrin and Dutton (1994) and the computational results of the present work in HRL.

A second peak is highlighted at 2500 Hz (St=0.27), which is normally associated with a shedding mechanism near the wake region. The two previous references also extracted a clear peak at similar frequencies (St=0.21 and 0.25). The mode for the longitudinal velocity is shown in Figure 8. The oscillations observed at the recompression region, also identified in Zhou et al. (2021), are related to the shedding mechanism. The computation of an azimuthal DFT combined to a power spectral density in the wake highlighted a dominant mode 1 at the identical Strouhal number which corresponds to a helical mode. This mechanism is well-known in subsonic and supersonic axisymmetric base flows.

The third dominant peak is identified at 11 kHz ($St = 1.18$) but a broader spectral peak could be considered, between $St = 0.5$ and 1.5. References refer to a higher frequency band which appear for the shear layer instabilities. The Figure 9 shows the corresponding mode for the longitudinal velocity and underlines the dynamics around the shear layer. This behavior could be associated with classical Kelvin-Helmholtz instabilities usually detected at high frequencies inside the shear layer.

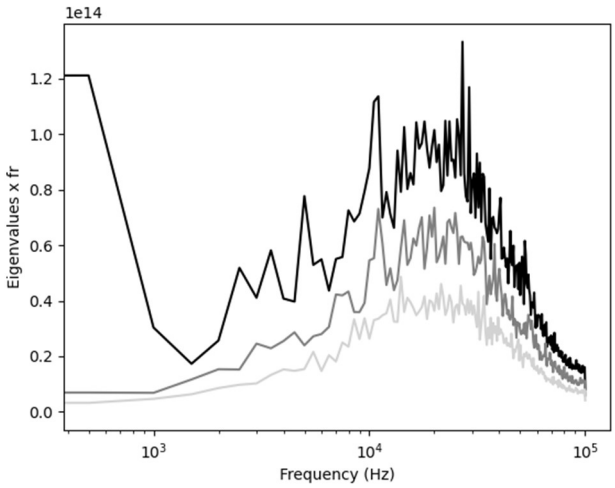

Figure 7. SPOD spectrum

The flow dynamics observed thanks to the SPOD analysis corresponds to what is found in the literature based on LES,

HRL, or experimental works. In this configuration, these three modes are dynamically interconnected. First, the shear layer ($St = 1.18$) generates vortical structures, then, the wake mode ($St = 0.27$) organizes large-scale motion and finally, the global mode ($St = 0.05$) modulates entire flow through feedback.

Discussion

The computational results show that the expansion fan is correctly captured by the newly defined sensor. The combination of the Ducros sensor and the modified Bhagatwala and Lele sensor is then validated for supersonic afterbody flows.

The modified inhibition function accomplishes its task by keeping the inception of the shear layer in LES resolution. Computational results at this location match well with experimental data, especially in terms of velocity fluctuation, which proves the efficiency of the function. It has been developed in order to better predict hypersonic flows, the application on a supersonic configuration is then a first step which has been validated.

The spectral analysis confirms the good resolution of the unsteady flow with the identification of typical mechanisms of axisymmetric afterbody flows. Nonetheless, the use of a larger number of snapshots could improve the resolution of the SPOD, mainly for the low frequencies.

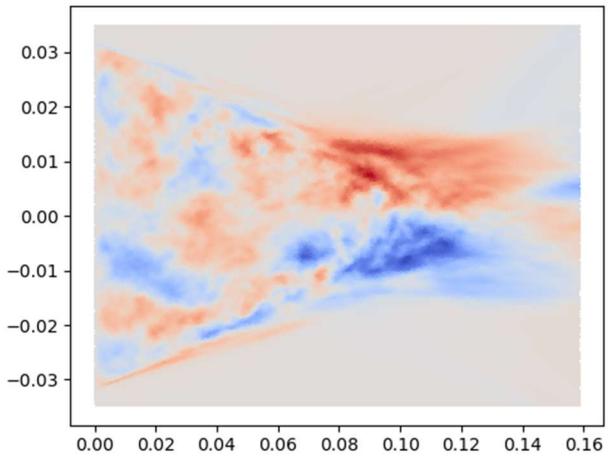

Figure 8. Mode at 2500 Hz for the longitudinal velocity u

CONCLUSION

In this study, we have confirmed the potential of HRL methods for improving the prediction of supersonic and hypersonic turbulent flows. By combining the robustness of RANS near-wall modeling with the resolving capabilities of LES, we have shown that HRL approaches can accurately capture key flow features such as separation, wake development, and unsteady behavior. The introduction of a new inhibition function tailored for supersonic and hypersonic flows has further enhanced the method's ability to handle complex flow phenomena.

Simulation results, validated against experimental data, highlight the advantages of HRL methods over traditional RANS approaches. The spectral analysis confirmed the resolution of unsteady flow dynamics, identifying dominant modes associated with global flow behavior, shedding mechanisms, and shear layer instabilities. These findings pave the way for the use of hybrid methods in the hypersonic regime, offering a promising compromise between computational efficiency and predictive accuracy. Future work will focus on refining these methods and applying them to more complex geometries and higher Mach numbers.

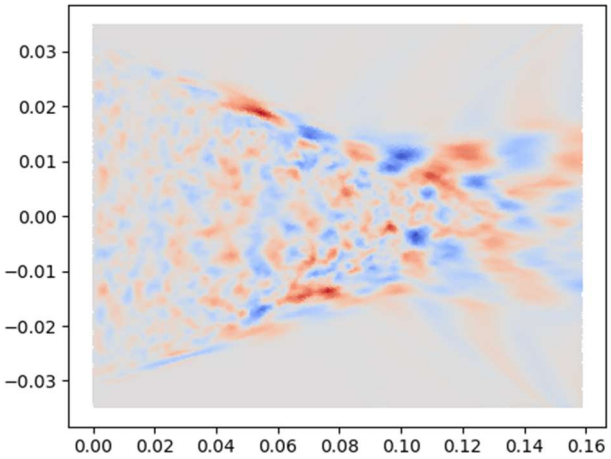

Figure 9. Mode at 11 kHz for the longitudinal velocity u

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