Large Eddy Simulations of a turbulent separation bubble to uncover the driving mechanism of the unsteadiness

Dynamics of turbulent separation bubbles – a linear modeling approach

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In Short

- A turbulent separation bubble occurs when a turbulent flow detaches from a surface and reattaches again downstream
- The low- and medium frequency unsteadiness in turbulent separation bubbles cause vibration and noise that lead to efficiency loss or mechanical fatigue in many engieneering systems
- Our goal is to apply global linear stability analysis and resolvent analyses to uncover the driving mechanism of the unsteadiness
- large eddy simulations will serve as data source for the analyses

Turbulent separation bubbles (TSB) are a complex flow phenomenon that occurs when the boundary layer of a fluid flowing over a solid surface separates from that surface due to adverse pressure gradients, curvature, or other factors. This separation can lead to the formation of a region of recirculating flow. This region is commonly referred to as separation bubble. Such flows occur in diffusers, air intakes, compressor and turbine blades, or simply behind steps and corners.

TSBs can be grouped into two categories: pressure-induced TSB which are produced by an adverse pressure gradient over a smooth surface (for example on an airfoil); and geometry-induced TSB which are caused by a geometric singularity, such as a backward-facing ramp. A simplified representation of a TSB over a backward-facing ramp is shown in Figure 1. The recirculation is also visible in the velocity fields of small scale RANS simulation of the a backward-facing ramp geometry that are shown in Figure 2.

Turbulent separation bubble flows exhibit strong unsteadiness over a large frequency range. Typically, the unsteadiness occurs in three frequency domains: a low-frequency unsteadiness, described as flapping or breathing, a medium-frequency unsteadiness, related to the shedding of coherent structures generated in the shear layer of the TSB, and high-frequency unsteadiness related to small-scale turbulence. The low- and medium frequency unsteadiness are at the centre of interest in this project. They are known to cause vibration, noise, mechanical fatigue, or even fluctuating thermal loads. In the diffuser of hydraulic reaction turbines, for example, unsteady flow separation has been linked to loss of efficiency. Unsteady separation may lead to unsteady forces on bluff bodies and corner flows. At higher speeds, TSB unsteadiness has been related to thermo-structural fatigue of inlet flows and combustor unsteadiness. Over the last decades, significant amount of research has been performed to better understand the low-frequency motion of geometry-induced TSBs. Detailed experimental and numerical investigations on backward-facing steps, fence-and-splitter-plate configurations, and blunt-plate flows, have shown that the reattachment line fluctuates at low frequency over the test surface. This has been attributed to the low-frequency flapping of the shear layer at the edge of the recirculation region. Pressure-induced TSBs, where the turbulent boundary layer separates because of an adverse pressure gradient, are much less common in the literature. This configuration is more complex compared to geometry-induced TSBs because the position of the separation front is free to fluctuate on the wall. Recent studies have shown that TSBs expand and contract in a low-frequency breathing motion. The term breathing was used because both the separation and reattachment fronts oscillate in opposite directions. Although TSB have been observed and described for several decades, the physical mechanisms behind the low- and medium-frequency unsteadiness are not yet fully understood. Some studies link the unsteadiness to mechanisms downstream of the turbulent separation bubble, other researchers have suggested that the bubble's low-frequency motion might be driven by large-scale coherent structures emanating from the upstream turbulent boundary layer. In the framework of stability theory, these two suspected origins of unsteadiness can be interpreted as two potentially different stability mechanisms. Hence, an in-depth investigation of these flows through global linear stability analysis and resolvent analysis in combination with data-driven modal decomposition are required for further progress in order to uncover the driving mechanism of the unsteadiness. As a data source for the analyses, highly resolved flow data is required. This data is acquired by running large eddy simulations (LES). In a LES, the large-scale eddies of a turbulent

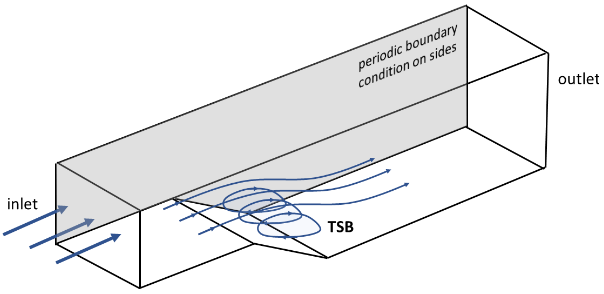

Figure 1: *Simplified representation of case geometry and TSB position*

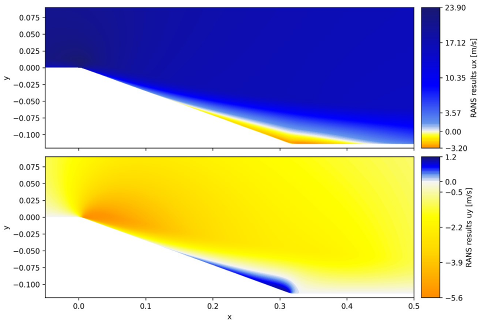

Figure 2: *RANS test simulation showing the velocity field at the TSB (streamwise velocity on top, and wall-normal on the bottom)*

flow are directly resolved, while the smaller, dissipative eddies need to be modelled. In this project we decided to use the software PyFR. PyFR is a highly scalable open-source software framework for solving complex fluid dynamics problems. It uses a high-order flux reconstruction scheme for solving partial differential equations (PDEs) governing fluid dynamics. It is designed to handle large-scale simulations on a wide range of computing architectures. PyFR does not employ explicit sub-grid scale models, instead it utilizes the numerical dissipation, which is commonly called model-free approach and therefore solves an implicit LES. PyFR is known for its high performance and excellent scaling behaviour when running large cases which is why it was selected for this project.

The geometrical setup of the LES conducted in the project consists of a straight duct as inlet, a bottom ramp that increases the cross-section of the flow (here the flow separates and a TSB occurs) and a straight duct downstream. As simplified representation of the geometry and where the TSB occurs is visualized in Figure 1. The same geometry which will be investigated in the LES is currently being investigated in experiments by Prof. Dr.-Ing Julien Weiss.

WWW

https://www.tu.berlin/en/flow/research/projects

More Information

[1] DFG project `https://gepris.dfg.de/gepris/projekt/504349109?context=projekt&task=showDetail&id=504349109&`

[2] A. Mohammed-Taifour, J. Weiss, Unsteadiness in a large turbulent separation bubble, *J. Fluid Mech.*, 799, 383-412. `doi:10.1017/jfm.2016.377`

[3] CFD software library `https://www.pyfr.org/`

Project Partners

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