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ASSESSMENT OF TURBULENCE CLOSURES FOR DETACHED FLOWS CONTROL

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Abstract. In this study, different turbulence closures are compared for the prediction of detached flows over a backward facing step, including a flow control device based on oscillatory suction and blowing. An automated optimization of the control parameters (frequency and amplitude) is carried out for the different closures, to assess the ability of Reynolds-Averaged Navier-Stokes (RANS) models to predict similar optimal parameters.

1 INTRODUCTION

Active flow control is an active research area for the last decade, which benefits from the progress of simulation methods, in terms of accuracy and robustness, and from the continuous increase of computational facilities. Actuator devices, such as synthetic jets or vortex generators, have proved their ability to modify the flow dynamics and represent a promising way to improve the aerodynamic performance of a system, without modifying its shape. However, the determination of efficient flow control parameters, in terms of location, frequency, amplitude, etc., is tedious and highly problem dependent. To overcome this issue, the numerical simulation of controlled flows is often considered to determine optimal control parameters, or at least a range of efficient parameters [1, 2]. However, several studies have shown that the simulation of controlled flows is a difficult task, because the actuation generates complex turbulent structures. Large Eddy Simulation (LES) is certainly the most appropriate approach for such problems [3], but the related computational burden makes its use tedious for optimization or exploration of control parameters. Reynolds-Averaged Navier-Stokes (RANS) models are more suitable in practice, but the results obtained may be highly dependent on the turbulence closure used. Therefore, the objective of the current study is to provide a rigorous and systematic assessment of some classical turbulence closures (Spalart-Allmaras, Launder-Spalding $k - \epsilon$, Menter SST $k - \omega$, EASM models) for RANS-based simulations with a synthetic jet actuation. The selected test-case corresponds to the flows over a backward facing step, for which an oscillatory suction and blowing jet is introduced to minimize the time-averaged recirculation length. The impact of turbulence closures is quantified for a range of actuation parameters (frequency, amplitude) and for a complete optimization process.

2 NUMERICAL METHODS

2.1 Simulation

The incompressible flow study is carried out with the ISIS-CFD solver, developed at LHEEA and available as a part of the FINE^{TM}/Marine computing suite. It solves incompressible Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. The solver is based on finite-volume method to build the spatial discretization and solves the conservation equations with a face-based cell-centered approach. All flow variables are stored at geometric centers of the arbitrary shaped cells. Surface and volume integrals are evaluated according to second-order accurate approximations by using the values of integrand that prevail at the center of the face f, or cell C , and neighbor cells C_{nb}. The fluxes are built using the AVLSMART scheme [4] in the Normalized Variable Diagram (NVD) context [5]. A pressure equation is obtained in the spirit of the Rhie and Chow SIMPLE algorithm [6]. Unsteady terms are solved using a dual-time stepping approach. In the case of turbulent flows, additional transport equations for modeled variables are discretized and solved using the same principles. For this study, the Spalart-Allmaras [7], the k-ε from Launder-Spalding [8], the k-ω-SST from Menter closure [9] and the Explicit Algebraic Stress Model (EASM) based on the k-ω closure by Gatski & Speziale [10] are used.

2.2 Optimization

When dealing with turbulent unsteady flows, the main issue for optimization is the computational burden. The evaluation of the cost function gradient using an adjoint approach is highly complex and the non-linear underlying phenomena may yield multi-modality. Furthermore, the optimization process may fail due to simulation errors (discretization, convergence, etc.), which make the evaluations noisy. To address these issues, the use of meta-models based on simulation results seems to be a promising approach [11]. In particular, the present work is focused on the Efficient Global Optimization (EGO) algorithm.

The EGO is a global optimization algorithm that makes use of a stochastic process model to drive the optimization [12]. As a first design of experiment phase, an initial database covering the bounded search space is generated from simulations. This database contains obviously the cost function values, but may also gather the error estimated for each evaluation. A stochastic model is constructed using this database, which allows to predict the cost function value in term of expectancy and variance at any point of the search domain. According to these predictions, the most interesting points are selected by means of a merit function. Once evaluated, the corresponding cost function values and the error estimations are added to the database. This process is repeated until convergence. Note that this approach can deal with noisy cost functions by prescribing a variance attached to each function evaluation. This feature is used to filter the numerical noise that can appear due to the time-averaging process[13].

3 TEST-CASE

The backward facing step is a well known test-case, studied by many researchers experimentally as well as numerically. This test-case is selected here to provide detached flows with a simple geometrical configuration. The configuration defined by Driver and Seegmiller [14] is used in this study. The backward-facing step geometry including a control device is defined on the Fig (1). The geometry and parameters are taken from the Driver case: $h = 0.0127$m, $U_{ref} = 44.2$m/s, $M_{ref} = 0.128$, the Reynolds number based on the boundary layer momentum thickness prior to the step is set to $Re_\theta = 5000$ and the boundary layer thickness at the inlet is $\delta_{BL} = 0.019$m. The control device is a suction / blowing jet with a diameter of $h/10$ and is located at $h/50$ from the step. The objective function for this test-case is the recirculation length of the time-averaged flow. A post treatment locates where the wall shear stress vanishes. As design parameters, we consider the jet amplitude and frequency, which are allowed to vary in the following intervals: $4\text{m/s} \leq U_{jet} \leq 50\text{m/s}$ and $50\text{Hz} \leq f_{jet} \leq 1000\text{Hz}$.

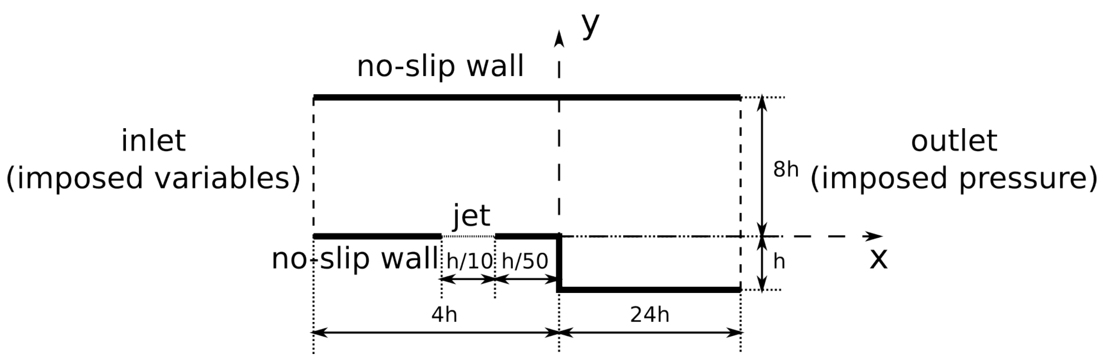

Figure 1: Backward-facing step configuration.

4 RESULTS

At first, we compare the results for the flow without actuation, which is used to initialize the simulation of the controlled flow over the backward-facing step. On the Fig. (2), the velocity profiles at different locations are represented, while the Tab. (1) gives the recirculation length for the different models. As seen, the k-ω SST Menter is the closest one to the experimental recirculation length value while the Spalart-Allmaras and k-ε Launder-Sharma underestimate it and the k-ω EASM overestimates the recirculation bubble length. The Spalart-Allmaras closure has the worst behavior concerning the velocity profiles.

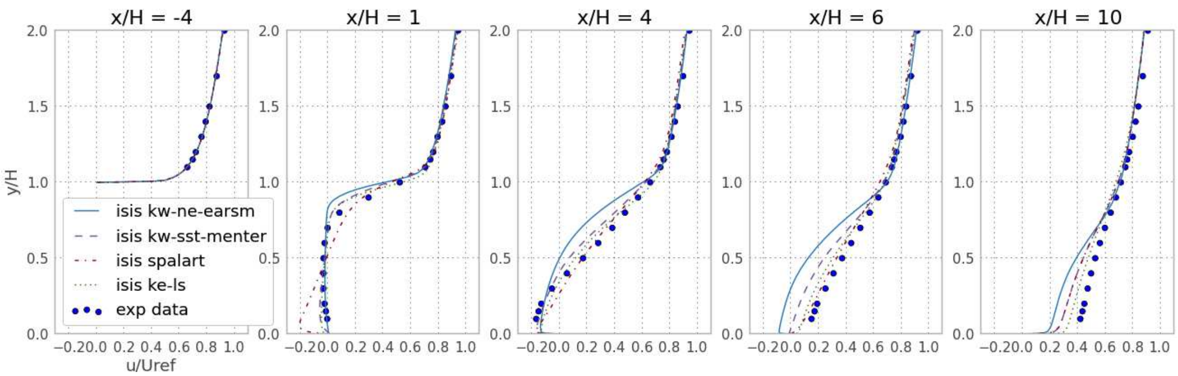

Figure 2: Initial velocity profiles at $x = -4$, $x = 1$, $x = 4$,$x = 6$ and $x = 10$ for different turbulence closures for the flow over the backward facing step without control.

Experimental	Spalart-Allmaras	k-ε Launder-Sharma	k-ω SST Menter	k-ω-ne-easm
6.26	6.05	5.41	6.37	7.56

Table 1: Comparison of recirculation length l/h computed against the experimental results from Driver and Seegmiller.

We consider then the results of the optimization process. A comparison of the models obtained with the different closures, with the simulated configurations, is depicted in Fig. (3). Obviously, the Spalart-Allmaras closure generates a very irregular flow response, that corresponds either to a vortex shedding process or to an attached recirculation bubble. The results obtained with the three other closures exhibit some similarities. Only one minimum is identified by the models, which is located in the same area in all cases. However, the precise values of the optimal control parameters are significantly different, as shown in Tab. (2).

The time-averaged turbulent kinetic energy fields, for the flow without actuation and with the best actuation found, are shown in Fig. (4) for the different closures. One can observe that all closures exhibit an increase of the turbulent kinetic energy level, with a very similar pattern. This seems to indicate that the most efficient actuations found rely on the same principle, even if the parameters depend on the closure.

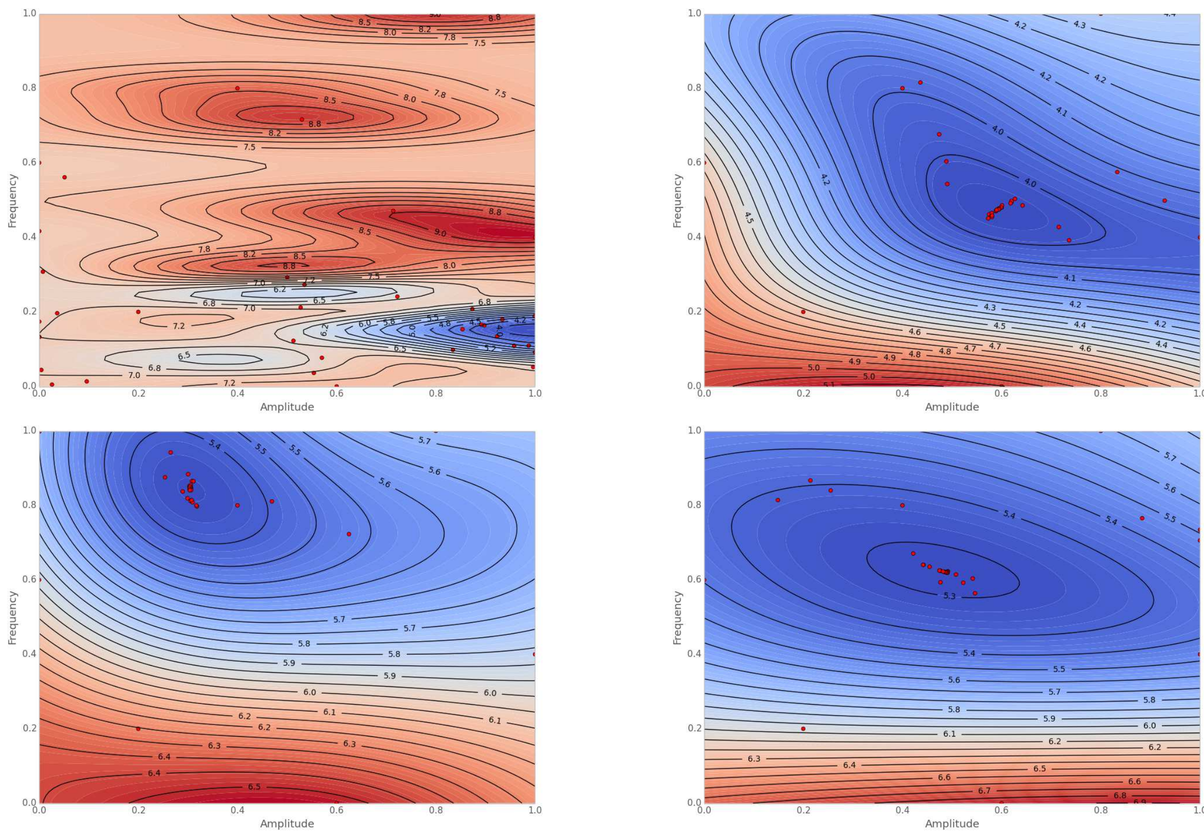

Figure 3: Recirculation length w.r.t. actuation parameters for the backward facing step case, for Spalart-Allmaras (top-left), Launder-Spalding $k-\epsilon$ (top-right), Menter SST $k-\omega$ (bottom-left), EASM (bottom-left) models, reconstructed from the optimization process.

	Spalart-All.	k-ε LS	k-ω SST	k-ω EASM
Frequency (Hz)	205	492	828	653
Amplitude (m/s)	50	31	18	25
Length / Length ini	0.69	0.72	0.84	0.70

Table 2: Comparison of optimal parameters and recirculation length found.

5 CONCLUSIONS

An assessment of different turbulence closures has been achieved in the context of separated flows with periodic actuation, for a backward facing step case. The comparison is not achieved for a single configuration, but for a full optimization of actuation parameters (frequency, amplitude) conducted using a surrogate model based optimizer.

It has been found that different optimal parameters are predicted by the closures, but similar flow modifications are observed in terms of turbulent kinetic energy increase.

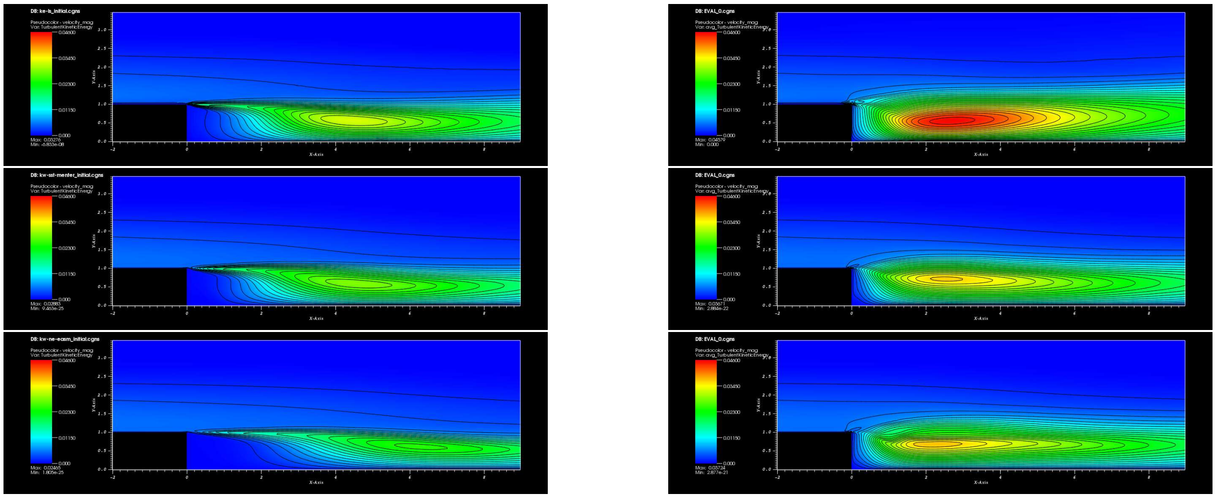

Figure 4: Time-averaged turbulent kinetic energy without actuation (left) and with best actuation (right), for Launder-Spalding $k-\epsilon$ (top), Menter SST $k-\omega$ (middle), EASM (bottom) models.

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