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INVESTIGATION OF THE FLOW OVER AN OSCILLATING CYLINDER WITH THE VERY LARGE EDDY SIMULATION MODEL

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Abstract. *The focus of this study is the numerical simulation of the forced oscillation of a circular cylinder with a Very Large Eddy Simulation model (VLES). Five different oscillating frequencies are considered to cover the so-called jump, where abrupt changes in drag and lift coefficients are observed. The results of the simulations are compared to available experimental data and numerical results from other studies.*

1 INTRODUCTION

The prediction of complex unsteady flows with a Direct Numerical Simulation (DNS) is too expensive in sense of computational costs, regardless of the advancements in computational technology over the past decades. DNS can only be applied to flows with very simple geometries and small Reynolds numbers, because a complete resolution of the turbulent structures is necessary. In contrary, with a Reynolds-Average-Navier-Stokes (RANS) model it is possible to simulate complex industrial problems, because all of the turbulent structures are modeled. However this approach shows problems with massively separating flows. Another possibility to simulate the turbulent flows is a Large Eddy Simulation (LES), where the big energy containing turbulent scales are resolved, while the small ones are modeled. In this case the computational costs increase very quickly with increasing Reynolds number. Because of these reasons in the last decade so-called hybrid turbulence models became increasingly popular. The underlying idea is to combine the advantages of different modeling approaches, more specifically, to deliver satisfactory results while demanding reduced computational costs. These new models also make it possible to solve complex industrial problems.

The Detached Eddy Simulation (DES) model, which was first proposed by Spalart [10] is the most popular hybrid turbulence model which has also been successfully used for many complex turbulent flow tasks. In this approach a RANS mode is applied near solid boundaries, while in separated flow regions and regions far from the wall the method switches to LES. The crucial issue in the application of DES is the "gray area", in which an undefined modeling zone exists. In this area the solution is neither pure RANS nor pure LES [7].

One of the new hybrid models, the so-called Very Large Eddy Simulation (VLES) model, was provided by Speziale [11]. This hybrid turbulence approach switches seamlessly between fully-modeled RANS and fully-resolved DNS modes depending on the numerical grid resolution. However, the original VLES model damps the Reynolds stress too much and requires a fine mesh resolution. Therefore, Han et al. [7] provided a modified VLES approach. This new hybrid model shows high efficiency and robustness in many applications already on relatively coarse grids [2], [7], [8].

Moving grid systems play an essential role in many engineering fields, for instance, for fluid-structure interaction. In such cases the problems become much more demanding in terms of computational cost [1]. Therefore, a reduction of computing times is especially important. Nowadays numerical investigations of such flows are rare, especially for hybrid turbulent models.

The focus of this study lies on the investigation of $k - \varepsilon$ and $\zeta - f$ VLES models in the context of moving grids. First, the VLES models are validated by computing the separating flow over periodic hills at a Reynolds number of $Re = 10,600$. Finally, the models are applied to investigate the flow over a forced oscillating circular cylinder at a Reynolds number of $Re = 10,000$. This simulation considers five different oscillating frequencies to cover the so-called jump, where abrupt changes in drag and lift coefficient are observed. The results of the simulation are compared to the available experimental data from [5] and numerical results from other studies.

2 VERY LARGE EDDY SIMULATION MODEL

2.1 CONCEPT

In the last twenty years hybrid turbulence models become more and more popular. They combine the advantages of different basic modeling techniques, such as RANS, LES or DNS.

In this study the Very Large Eddy Simulation (VLES) approach from Chang [2] is investigated. This hybrid turbulence model provides a transition from the fully-modeled RANS to the fully-resolved DNS modes depending on the numerical grid resolution. For the switching between these models in the VLES approach the Reynolds stress of a generalized RANS model is rescaled through a so-called resolution control function F_r:

$$\tau_{ij}^{sub} = F_r \tau_{ij}^{RANS}. \tag{1}$$

F_r depends on the two length scales: the turbulent length scale L_c related to the spectral cut-off and the integral length scale L_i ($\propto k^{3/2}/\varepsilon$):

$$F_r = min\left[1, \left(\frac{L_c}{L_i}\right)^{\frac{3}{4}}\right]. \tag{2}$$

F_r takes on a value between one and zero. When F_r approaches zero, then (theoretically) all of the scales are resolved and the VLES model behaves like a DNS. In the near-wall region $F_r \to 1$, as in the case of a coarser mesh and the model works as a RANS model, similar to the DES concept. In [2] a detailed description of the VLES approach and the resolution control function F_r can be found.

2.2 COMPATIBILITY WITH RANS MODELS

The VLES model is well compatible with different RANS turbulence models. In this study a VLES approach based on two different RANS models is used: the $k-\varepsilon$ VLES model based on the Chien $k-\varepsilon$ model [3] and the elliptic-relaxation eddy-viscosity $\zeta - f$ VLES model [9]. The $\zeta - f$ RANS model developed by Hanjalic et al. [9] uses a transport equation for the velocity scale ratio $\zeta = \overline{v^2}/k$ and an equation for the so-called elliptic relaxation function f, in addition to the equations for the turbulent kinetic energy k and its dissipations rate ε:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)\right], \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{C_{\varepsilon_1} P - C_{\varepsilon_2}\varepsilon}{T} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)\right], \tag{4}$$

$$\frac{\partial \zeta}{\partial t} + u_j \frac{\partial \zeta}{\partial x_j} = f - \frac{P}{k}\zeta + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\zeta}\frac{\partial \zeta}{\partial x_j}\right)\right], \tag{5}$$

$$L^2 \Delta f - f = \frac{1}{T}\left(C_1 + C_2 \frac{P}{\varepsilon}\left(\zeta - \frac{2}{3}\right)\right). \tag{6}$$

The corresponding turbulent viscosity is defined as

$$\nu_t = C_\mu^\zeta \zeta k T, \tag{7}$$

where T is the turbulent time scale and C_μ^ζ is a model constant. The coefficients and a detailed description of this model can be found in [8].

This eddy-viscosity-based model yields better results in comparison to other RANS models for wall-bounded flows [8]. Since the predictive accuracy of VLES depends on the specific RANS turbulence model [6], the application of the $\zeta - f$ model as a background RANS model for VLES appears to be promising.

Compared to basic RANS models, in the VLES approach only the formulation of the turbulent viscosity is modified. For example, for the $\zeta - f$ model the turbulent viscosity takes the form

$$\nu_t = F_r C_\mu^\zeta \zeta k T. \tag{8}$$

2.3 NEW FILTER WIDTH

The definition of the resolution control function F_r contains the turbulent cut-off $L_c = C_x\Delta$, which depends on the filter width Δ. The filter width determines the value of the resolution control function and therefore implies a kind of interface between RANS and DNS. Thus, the choice of the expression for Δ may play an important role, especially in the case of strongly anisotropic grids.

In the original VLES model the standard LES filter-width $\Delta_{vol} = (\Delta_x\Delta_y\Delta_z)^{1/3}$ is used. In the present work the behavior on the VLES model is investigated with a modified filter width, the so-called IDDES filter width, which was introduced by Travin [13] for the Detached Eddy Simulation model:

$$\Delta_{IDDES} = min(max[C_w d_w, C_w h_{max}, h_{wn}], h_{max}), \tag{9}$$

where d_w is the distance to the wall, h_{wn} is a grid distance in the wall-normal direction, h_{max} is a maximum local grid spacing and $C_w = 0.15$ is a constant.

3 FLOW OVER THE PERIODIC HILL

For validation of the VLES model on a static grid the flow over a two-dimensional periodic hills at a Reynolds number of $Re_b = 10,600$ based on the bulk velocity is considered. In this flow the separation is not clearly determined by the geometry, therefore, it is especially challenging to predict the correct separation point.

The size of the computational domain is defined as $L_x = 9h, L_y = 3.036h$ and $L_z = 4.5h$, where h is the hill height. On the top and bottom edges of the domain the wall boundary condition is applied, while a periodic boundary condition is used in the streamwise and spanwise directions. The computational domain with the 80x100x30 mesh is shown in the figure 1. The results are compared with reference LES data [12] obtained by a highly-resolved simulation with $4.6 \cdot 10^6$ grid nodes.

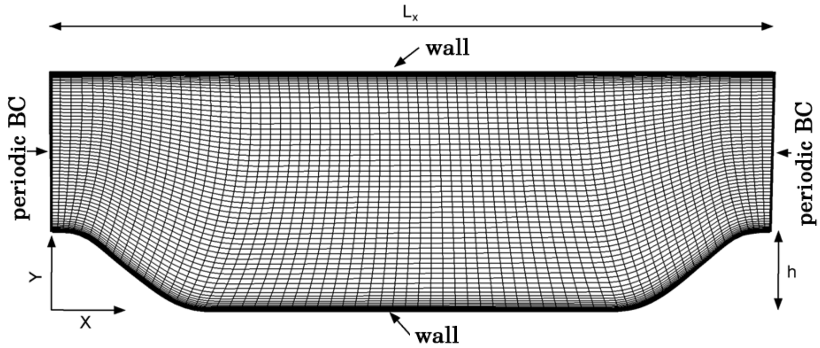


Figure 1: The flow over the two dimensional periodic hills. Computational domain and mesh

The flow separates on the top of the hill and a recirculation zone generates in the downstream of the hill side.The detailed separation and reattachment positions obtained with the different models are shown in the table 1. The VLES approach predicts the position of the separation well even on the coarse grid compared to the LES.

The velocity profiles for the VLES $k-\varepsilon$ model in comparison to the reference data are shown in figure 2. It can be seen that the VLES simulation shows very good agreement with the LES reference results.

Model	x_s	x_r
LES [12]	0.22	4.72
VLES $k - \varepsilon$ (Δ_{vol})	0.18	4.48
VLES $k - \varepsilon$ (Δ_{IDDES})	0.20	4.65
VLES $\zeta - f$ (Δ_{vol})	0.20	4.62

Table 1: Separation and reattachment points for different models

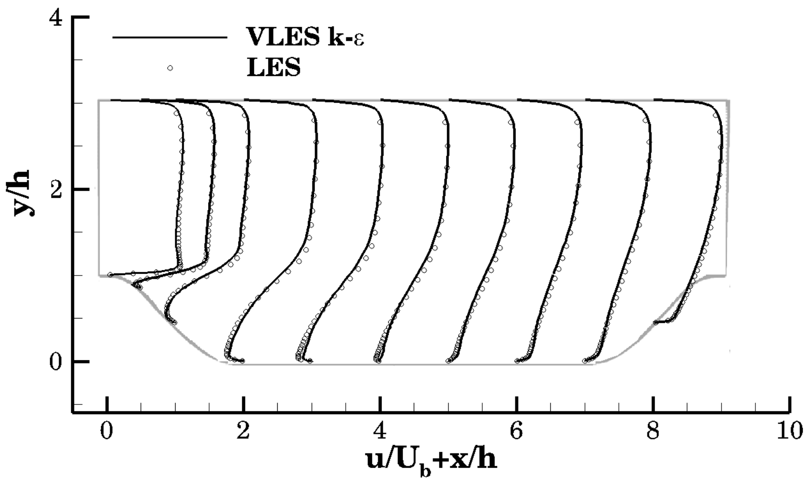


Figure 2: Velocity profiles for the LES and the VLES $k - \varepsilon$ models

With the IDDES filter width the $k - \varepsilon$ VLES approach yields better results than with the standard Δ_{vol} filter width (see table 1).

4 FLOW OVER THE OSCILLATING CYLINDER

Next the flow past an oscillating circular cylinder is investigated. The Reynolds number is $Re = 10,000$ based on the inflow velocity U and the cylinder diameter D.

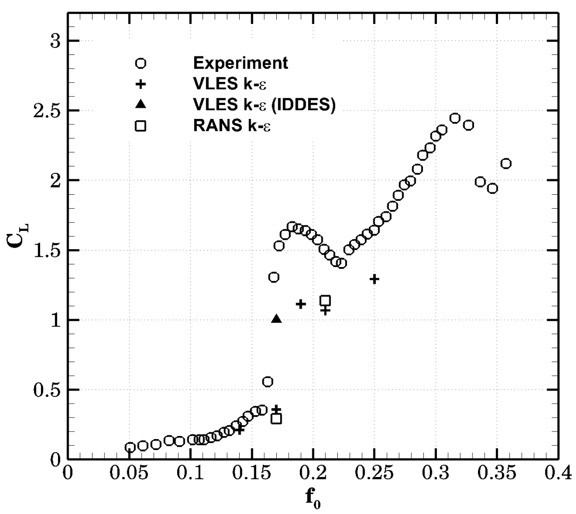
The following equation describes the cylinders displacement in the cross flow direction:

$$y = Y_0 \sin(2\pi f_0 t), \tag{10}$$

where Y_0 is the cylinder displacement amplitude and f_0 is the oscillation frequency of the cylinder.

To cover the abrupt changes in drag and lift coefficients in this simulation five different oscillating frequencies $f_0 D/U = 0.14; 0.17; 0.19; 0.21$ and 0.25 are considered. The results are compared to the experimental data from Gopalkrishnan [5]

The lift and drag coefficients C_L and C_D are presented in figure 3 as a function of the dimensionless frequency for the $k - \varepsilon$ VLES model. This model captures the sharp change in the lift coefficient around the vortex shedding frequency. It under-predicts the value of C_L for oscillation frequencies $f_r > 0.17$, while the value at the low frequency of $f_r = 0.14$ shows good agreement with the experiment data from Gopalkrishnan [5]. For comparison also the results for the lift coefficient for the $k - \varepsilon$ RANS model are given for two frequencies i.e. $f_r = 0.17$ and $f_r = 0.21$. As figure 3 (right) shows, this model yields results that are very similar to the VLES model results for both frequencies.



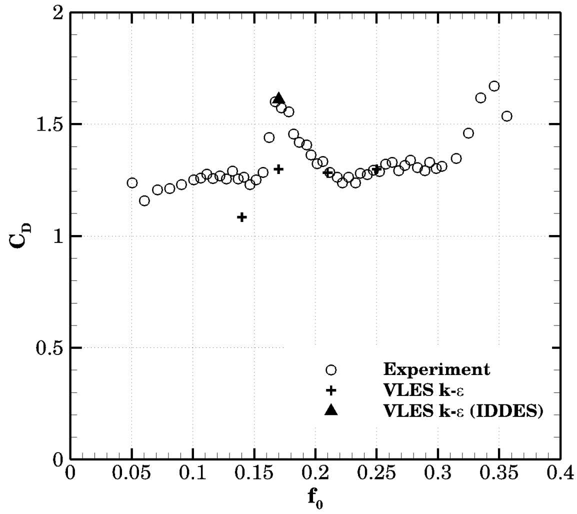


Figure 3: Lift and drag coefficients as a function of non-dimensional frequency for the $k - \varepsilon$ VLES model

To see the influence of the filter width on moving grid simulations, results for the $k-\varepsilon$ VLES with the IDDES filter are given for the oscillation frequency $f_r = 0.17$ in in figure 3. In this case the results show a better agreement with experimental data, in comparison to the standard $k - \varepsilon$ VLES.
The agreement between the simulation results for the VLES model and the experimental data for the drag coefficient is reasonably good (see figure 3, right). The standard VLES under-predicts the drag coefficient at low frequencies, but for higher frequencies the prediction is fairly accurate. While the prediction of the drag coefficient with the IDDES filter width in VLES, shows a very good agreement with the experimental data for the investigated frequency of $f_r = 0.17$.

The results from the $\zeta - f$ VLES model have similar characteristics (figure 4) as for the $k-\varepsilon$ VLES model. The lift coefficient is under-predicted for higher frequencies, while the drag coefficient is in very good agreement with the experimental data, without the application of the modified filter width Δ_{IDDES}.

5 CONCLUSION

In this study the $\zeta - f$ and $k - \varepsilon$ VLES models were investigated for the moving grids. Firstly, both models are validated with a static grid test-case. The flow over a periodic hill at $R_e = 10,600$. It was shown that the results of the VLES model can be improved by the introduction of the new IDDES filter width instead of the standard volume filter width. Subsequently both models were applied on a moving grid test-case, where the flow past a harmonically oscillating circular cylinder has been investigated at a Reynolds number of $Re = 10,000$. It was shown that the $\zeta - f$ and $k - \varepsilon$ VLES model can predict the abrupt changes in drag and lift coefficients. The values of the lift coefficient were under-predicted for both VLES models, while the values for the drag coefficient were in very good agreement with the reference data. The results on the moving grid, as on the static grid, can be improved by applying the IDDES filter width in the expression for the resolution control function F_r.

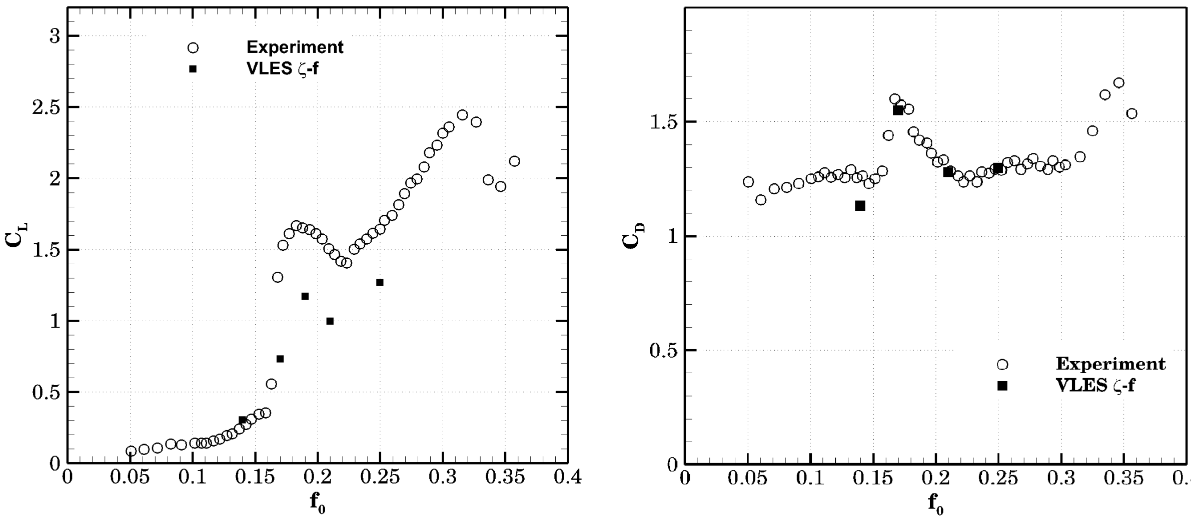


Figure 4: Lift and drag coefficients as a function of non-dimensional frequency for the $\zeta - f$ VLES model

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REFERENCES

[1] Bunge, U. Numerische Simulation turbulenter Strömungen im Kontext der Wechselwirkung zwischen Fluid und Struktur. *Univ.-Verlag der TU, Univ.-Bibliothek*, 2005

[2] Chang, C. Y., Jakirlic, S., Dietrich, K., Basara, B. and Tropea, C. Swirling flow in a tube with variably-shaped outlet orifices: An LES and VLES study. *International Journal of Heat and Fluid Flow*, 49 pp. 28-42. 2014

[3] Chien, K.-Y. Predictions of Channel and Boundary-Layer Flows with a Low-Reynolds-Number Turbulence Model, *AIAA Journal*, Vol. 20, No. 1, pp. 33-38, 1982.

[4] Dong, S., and Karniadakis, G. E. DNS of flow past a stationary and oscillating cylinder at. *Journal of Fluids and Structures*, 20.4 pp. 519-531, 2005.

[5] Gopalkrishnan, R. Vortex-induced forces on oscillating bluff cylinders. *WOODS HOLE OCEANOGRAPHIC INSTITUTION MA*, No. WHOI-92-38, 1993.

[6] Han, X., and Krajnović, S. A new very large eddy simulation model for simulation of turbulent flow. *Progress in Hybrid RANS-LES Modeling*. Springer Berlin Heidelberg, pages 131-140, 2012.

[7] Han, X. and Krajnović, S. Validation of a novel very large eddy simulation method for simulation of turbulent separated flow. *International Journal for Numerical Methods in Fluids*, 73(5), pages 436-461, 2013

[8] Han, X. and Krajnović, S. An efficient very large eddy simulation model for simulation of turbulent flow. *International Journal for Numerical Methods in Fluids*, 71(11), pages 1341-1360, 2013

[9] Hanjalić, K., Popovac, M. and Hadžiabdić, M. A robust near-wall elliptic-relaxation eddy-viscosity turbulence model for CFD. *International Journal of Heat and Fluid Flow*, 25(6), pages 1047-1051, 2004

[10] Spalart, P. R., Jou, W. H., Strelets, M., and Allmaras, S. R. Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach. *Advances in DNS/LES, 1*, pages 4-8, 1997

[11] Speziale, C. Turbulence modeling for time-dependent RANS and VLES: a review.*AIAA Journal*, 36(2), pages 173-184, 1998

[12] Temmerman, L. and Leschziner, M. A. Large eddy simulation of separated flow in a streamwise periodic channel constriction. *TSFP DIGITAL LIBRARY ONLINE. Begel House Inc.*, 2001.

[13] Travin, A. K., Shur, M. L., Spalart, P. R. and Strelets, M. K. Improvement of delayed detached-eddy simulation for LES with wall modelling. *ECCOMAS CFD 2006: Proceedings of the European Conference on Computational Fluid Dynamics, Egmond aan Zee, The Netherlands, September 5-8*, 2006. Delft University of Technology; European Community on Computational Methods in Applied Sciences (ECCOMAS), 2006.