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Numerical simulation of the fluid–structure interaction in a tube array under cross flow at moderate and high Reynolds number

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ABSTRACT

The unsteady loads in a tube bundle are studied at moderate and high Reynolds number by means of URANS and hybrid (DDES) modelling. The onset of fluid-elastic instability is analysed for different structural parameters, Scruton number and reduced velocity. The simulations have been carried out with the code NSMB (Navier–Stokes Multi Block) by using turbulence modelling methods URANS and DDES (Delayed Detached Eddy Simulation). The CEA-DIVA configuration is considered for the cylinders array for an inter-tube Reynolds number 60 000. The study is carried out for a configuration of (4×5) cylinders in static conditions as well as for the vertical free motion of one of the central cylinders in one DOF (Degree Of Freedom).The inter-tube Reynolds number is 60 000. It is found that this cylinder spontaneously displays an oscillatory motion which first corresponds to Vortex Induced Vibration (VIV), associated to a lock-in mechanism for low values of the reduced velocity and secondly develops Movement Induced Vibration, MIV, for higher values of the reduced velocity. The variation of the cylinder's oscillations frequency, of the unsteady loads and the structure's displacement are studied as a function of the reduced velocity for low and high values of the Scruton number. The increase of the phase-lag between the forces and the displacement is predicted and discussed for different Scruton number values and reduced velocities.

1. Introduction

The prediction of fluid-elastic instabilities developed in a tube bundle is of major importance for the design of heat exchangers for vapor cooling in nuclear reactors and for the prevention of accidents associated with material fatigue, shocks between beams and severance of the solid walls. The fluid-elastic instabilities leading to flutter in tube-arrays appear in the laminar regime and persist as far as the turbulent regime. This kind of galloping instability has been identified for the past forty years. However, little has been achieved in the domain of detailed numerical simulations for the prediction of the

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unsteady loads and of the displacement of the solid structure. Many studies have been devoted to enhancing understanding and to offer phenomenological models for the design. A considerable number of this kind of models have been developed since the work of Connors (1970), Blevins (1974, 1979), Tanaka and Takahara (1981, 1982), Chen (1983), Paidoussis and Price (1988) and Lever and Weaver (1982) among others.

Explaining and understanding the instability onset and its dependence on the flow-structure parameters such as the reduced velocity and Scruton number increase are an important aspect concerning fundamental phenomena in the domain of fluid–structure interaction. A key point for the understanding of this instability is related to the appearance of negative damping which comes from the fluid forces interacting with the structure. This occurs when the transverse flow velocity increases, where the phase difference between the force applied by the fluid and the cylinder's movement changes sign and results in a sign change of the apparent damping, thereby creating fluid-elastic instability. The main problem is to correctly evaluate this phase shift model. Despite various modelling attempts, the question remains open, as noted by Weaver (2008): “Despite more than 40 years of research, this mechanism is not fully understood”. However quasi-static models are used to characterize the instability in high Scruton numbers Scruton ($Sc > 30$) and in two or more degrees of freedom. For low Scruton numbers, the instability develops already for a single degree of freedom. This phenomenon can be modeled by taking into account a delay time between the movement and the efforts. The pure delay model is “amnesia.” Granger and Paidoussis (1996) proposed a model “with memory” of first or second-order with respect to the time constants.

In the industrial context, the high Reynolds number causes a complex interaction between the instability due to the movement of the solid structure and the near-wall unsteady turbulence around the cylinders. To take sufficient account of this interaction and to accurately predict the unsteady loads, it is necessary to use reliable turbulence modelling approaches. These methods have to simultaneously include the low frequency organised motion effects associated with the structure's movement and the fluid's coherent vortices as well as the random turbulence effects. In this context, approaches such as Unsteady Reynolds Average Navier–Stokes (URANS), derived from turbulence in statistical equilibrium assumptions, tend to underestimate the global coefficients (drag, lift) and their amplitudes (see collected papers after the European research program “Detached Eddy Simulation for Industrial Aerodynamics” (DESIDER), Haase et al., 2009).

The Large Eddy Simulation (LES) is appropriate and offers a rich physical content in the moderate Reynolds number range. However, this approach is mandatorily 3-D and quite costly for design purposes at this stage. On the other hand, in higher Reynolds numbers it becomes more difficult to apply it by using realistic grid sizes, in respect to industrial design requirements. In this flow category, it is noticeable that the upstream nominal Reynolds number based on the free-stream velocity corresponds to a *much higher* inter-tube Reynolds number which can be three or four times higher than the nominal Re, depending on the pitch distance. Therefore, a ‘moderate’ upstream Reynolds number flow for the cylinders array corresponds to a high Reynolds range in the flow physics context. These facts have to be considered for the CFD method choice in the Computational Fluid Dynamics-Computational Structural Mechanics (CFD-CSM) coupling.

Hybrid RANS-LES methods are quite suitable for this category of fluid-elastic instability problems, because they associate the benefits of URANS in the near-region and those of LES in the regions of flow detachment. In particular, the Delayed Detached Eddy Simulation (DDES), Spalart et al. (2006) is a hybrid method which is successfully used for strongly detached unsteady flows as reported by the collected papers of the fourth ‘Hybrid RANS-LES Methods’ (HRLM) symposium, Fu et al. (2012). DDES can be considerably improved by using adapted URANS modelling in the near-wall region and adapted LES modelling in the flow detachment areas, in order to allow for modification of the turbulent scales accounting for non-equilibrium turbulence. In this context, improved approaches can be used to take account of these effects, as for example the Scale Adaptive Simulation (SAS), Menter and Egorov (2005), Menter and Bender (2003), the Organised Eddy Simulation (OES), Braza et al. (2006) and Bourguet et al. (2008) among others. SAS adapts the Kolmogorov turbulence scale according to flow regions governed by non-equilibrium turbulence effects. OES accounts for stress–strain directional misalignment in non-equilibrium turbulence regions thanks to a tensorial eddy-viscosity concept derived from Differential Reynolds Stress Modelling (DRSM) projection on the principal directions of the strain-rate tensor.

The current efforts in turbulence modeling are devoted to accurately reproduce the flow physics with respect to instability amplification, of strong flow detachment and to accurately predict the associated frequencies and unsteady load fluctuations. Although a significant progress has been accomplished in the last decade, there still remain open questions with regard to the prediction of the above mechanisms with the accuracy required by the design and in particular of these mechanisms modification due to the fluid–structure coupling. To our knowledge, there do not exist predictions of vibration instability in the high-Reynolds number range by using efficient CFD and producing new results in this area. In particular, the progressive development and assessment of the phase-lag between the forces and the displacement of the solid structure from the Vortex Induced Vibration (VIV) state towards the Movement Induced Vibration (MIV) dynamics are among the main objectives of the present study. Therefore, the present paper mainly focuses on new results obtained by means of efficient CFD with regard to the physics of Flow Induced Vibration (FIV) in a cylinders bundle in a Reynolds number range corresponding to industrial applications. An exhaustive comparison of turbulence models is not presented in this paper. Only selected models from the previously mentioned state-of-the-art, able to deal with strong unsteadiness, with high-Reynolds number effects and with predominant instabilities, are considered and coupled with efficient numerical schemes. The purpose of a first part of the present study is to select among these few models, the most appropriate for the static-case unsteady flow simulations, in order to use them in the dynamic case simulations of FIV (central cylinder allowed for one degree of freedom vertical motion). Furthermore, a special attention is paid to examine the predictive capabilities of the finally selected modelling in two- and three-dimensions for the dynamic case at high Reynolds number. In the physical