Discrete Bubble Dynamics Modeling

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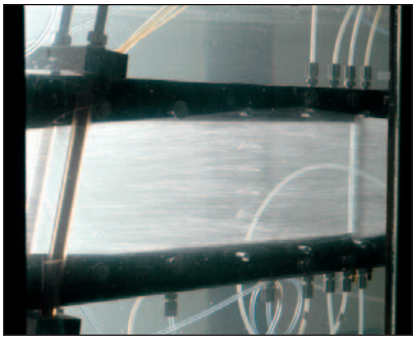
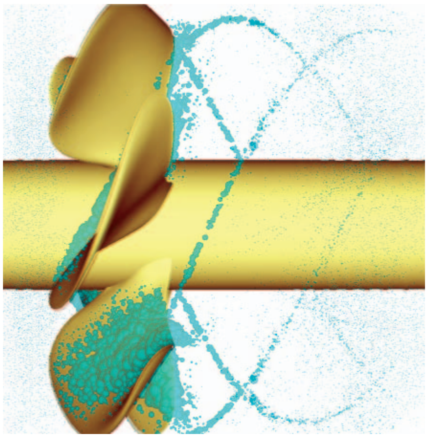
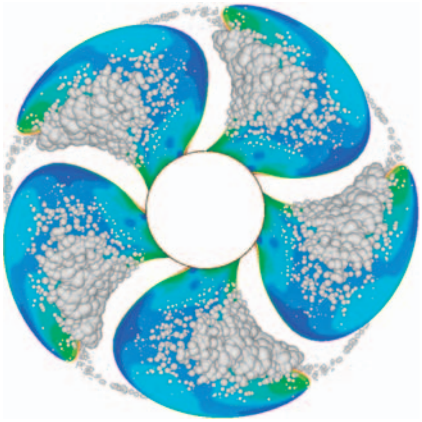


Bubbly flow in a channel observed in DYNAFLOW's laboratories



Bubble field simulation around a propeller using an actual nuclei size distribution as measured in the ocean shows where the bubbles become large (and thus visible to human eyes as cavitation)

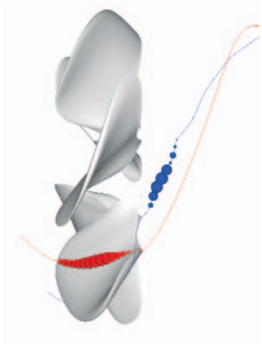


Contours of pressure distribution on the blade surfaces in the presence of bubbles

CONTRARY TO COMMON BELIEF, it is practically impossible to have a pure liquid devoid of bubble nuclei. These are omnipresent in microscopic sizes in all liquids found in our everyday life and in engineering applications. While for many applications these bubble nuclei have no impact and can be ignored in CFD simulations, there are flow fields where the presence and dynamics of these bubbles profoundly affect the problem at hand. They could result in hydrodynamic noise (such as routine faucet noise), materials erosion, and degradation of performance [1]. When controlled, they can also be exploited for drag reduction, chemical reaction enhancements, disinfection, propulsion improvements, materials cleaning, cutting, and noise decay [1]. Bubbles affect the flow significantly when they experience regions of high pressure and/or velocity variations. In such applications, treating the bubbles as discrete entities and tracking their motion and deformation may provide important insight to the design engineer.

One example where a discrete bubble model is very useful is the determination of cavitation inception on advanced equipment design, such as turbomachinery. In a CFD flow field, a commonly used criterion is that cavitation occurs wherever the liquid pressure drops below the vapor pressure. This assumption fails if the liquid is not supersaturated with nuclei and is particularly problematic for a design that aims to avoid cavitation completely. When a microscopic bubble nucleus encounters a large negative pressure gradient in the liquid flow, it expands. Depending on the dynamic balance between the pressures generated by the bubble gas content, the surface tension, and the inertia of the liquid, the bubble may grow explosively, exceeding its equilibrium volume, and then collapse violently, generating high acoustic and dynamic pressures. Accurate prediction of bubble dynamics is also very important in underwater acoustics computations because volume-changing bubbles are a major source of underwater noise.

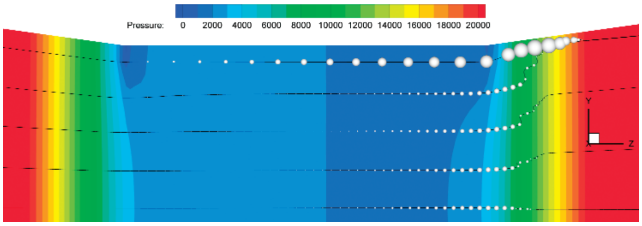
DYNAFLOW, Inc. has conducted extensive studies on non-spherical bubble dynamics and interactions with solid and free boundaries, vortical flow structures, and other bubbles. From these studies, a simplified Surface Averaged Pressure (SAP) spherical bubble dynamics model and a Lagrangian bubble tracking scheme [2] have emerged. In the SAP scheme, the pressure and velocity of the surrounding flow field are averaged on the bubble surface, and then used for calculations of the bubble motion and volume dynamics. This produces a remarkably accurate simulation of the bubble dynamics, especially when the bubble is captured by a



Bubble tracking results obtained from a DBM simulation. Inflow is from left to right, and the bubbles are seen from propeller-fixed coordinates. The red bubble cavitates over the suction side of the blade, while the blue bubble cavitates inside the tip vortex

vortex, and brings the spherical bubble dynamics results very close to the more sophisticated 3D and axisymmetric simulations that include non-spherical deformation of the bubbles and extreme behavior, such as reentrant jets and bubble splitting [3]. The model was validated through extensive experimental and numerical studies on the cavitation inception of Navy propulsors [4]. This model, embodied in DYNAFLOW's commercial software DF_Multi_Sap© [4] which needs an externally provided pressure and velocity field unless coupled with other codes, is now available to FLUENT users as the Discrete Bubble Model (DBM) user-defined function (UDF). The DBM works seamlessly with FLUENT to simulate the presence of bubble nuclei or purposely injected bubbles, and obtain the behavior of the bubbles and the associated acoustic noise. The DBM tracks individual bubbles and works in a manner similar to the discrete phase particle tracking module (DPM).

The DBM module is available through FLUENT's graphical user interface (GUI) for the DPM, including the definition of bubble injections. The bubble motion equation used in the DBM is compatible with the DPM sub-models and options. For example, users can select their choice of drag model, lift force, and time-stepping schemes. The bubble dynamics portion can be solved using an incompressible liquid-modified Rayleigh-Plesset equation or a compressible liquid-modified Gilmore equation. The postprocessing can be done through FLUENT's GUI with an option to generate additional output files that store bubble history.



DBM simulation of 100 µm diameter (initially) bubbles through a venturi under a condition very close to cavitation inception. The bubble along the center (bottom track) grows slightly, but the bubble near the wall (top track) grows much larger and abruptly collapses

The DBM UDF is a suitable tool for studies of cavitation inception for hydrofoils and turbomachinery, bubble nuclei effects, bubble noise, and propulsion modification. It can be used for many practical problems in industrial and naval applications associated with flows in pipes, jets, pumps, propellers, ships, and the ocean. For example, DYNAFLOW has been using this tool in on-going efforts supported by Office of Naval Research (ONR) on propeller cavitation, wake signatures of waterjet propelled ships, bubble-wake interactions, cavitating jet models, and bubble entrainment around a ship.

The DBM software is currently under further development to include the effects of gas diffusion, heat transfer, evaporation and condensation, bubble splitting and coalescence, and two-way interaction between the bubbles and the flow field. ■

More info @ www.dynaflow-inc.com

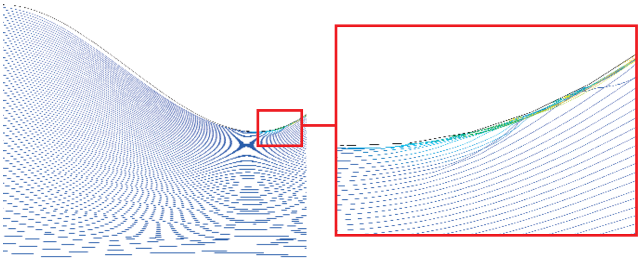
References

1 Brennen, C.E.: Cavitation and Bubble Dynamics, Oxford University Press, New York, 1995.

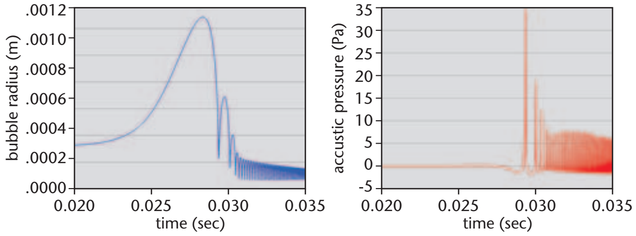
2 Hsiao, C.-T; Chahine, G.L.; Liu, H.: Scaling Effects on Prediction of Cavitation Inception in a Line Vortex Flow; Journal of Fluids Engineering, 125, 53-60, 2003.

3 Choi, J.-K.; Chahine, G.L.: Noise due to Extreme Bubble Deformation near Inception of Tip Vortex Cavitation; Physics of Fluids, 16 (7), 2411-2418, 2004.

4 Hsiao, C.-T; Chahine, G.L.: Scaling of Tip Vortex Cavitation Inception Noise with a Bubble Dynamics Model Accounting for Nuclei Size Distribution; Journal of Fluids Engineering, 127, 55-65, 2005.



Bubble trajectories inside a parabolic nozzle (left), with magnification of the region near the throat (in the red box) (right). The flow is from left to right and the color represents the bubble size. Large bubbles are observed just past the throat, where the onset of cavitation is predicted



Bubble diameter (left) and the acoustic noise (right) from a bubble passing through a Venturi nozzle, simulated by the DBM in FLUENT