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Exploiting SIMD vectorisation for unstructured high-order scale resolving simulations

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Computational modelling is now firmly established as part of modern engineering design. This is especially true in fields such as aviation and turbomachinery, where the strive for increased aeronautical efficiency means that engineers are increasingly in need of high-fidelity simulations to understand the influence of even small design changes on overall aerodynamic performance. A step towards this is to consider moving away from present industry-standard techniques such as RANS, which is implemented at the heart of most commerical software, towards transient large eddy simulations (LES), which offer increased fidelity with an associated increase in computational cost. To enable LES simulations in reasonable timescales therefore requires an increase in solver speed that, to date, commercial software has not been able to provide, despite dramatic increases in the calculation power of modern computational hardware.

A promising route towards the goal of routine high-fidelity simulations is the use of higher-order methods. The increased arithmetic intensity of such discretisations allows them to overcome the memory bandwidth bottlenecks present in modern many-core hardware. In particular, the use of matrix-free methods, which avoid the generation of dense local matrices, alongside efficient sum-factorisation evaluation techniques and use of SIMD vectorisation such as AVX2 and AVX512 to fully exploit computational power, is now a central focus of the high-order community [2, 3, 4]. So far however, only quadrilateral and hexahedral elements have been considered under this regime. Although these elements offer exceptional performance, from a practical perspective, it is difficult at best to construct all-hexahedral meshes for the complex geometries that are relevant from an industrial perspective. Unstructured meshes of triangles, tetrahedra and prisms therefore offer an alternative route to avoid this issue, but in the classical spectral element formulation using Lagrange interpolants, this leads to a non-tensorial expansion in shape functions, thereby losing the performance gains found by using sum-factorisation.

In this talk, we demonstrate how an alternative choice of high-order tensor-product basis [1] can be combined with explicit SIMD vectorisation in order to construct an efficient matrix-free discretisation of elliptic operators for mixed element types. We present the results of a performance analysis on modern CPU architectures from [5] that demonstrates the efficacy of this scheme when applied to complex geometries, and discuss the relative performance of this approach between various element types.

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