Using 3D Image Data Beyond Visualization for NDE and Material Characterization: Numerical Analysis Techniques

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Abstract

Image-based modelling technology represents a fast-growing tool for using 3D image data such as CT, micro-CT and SEM as the basis for finite element and computational fluid dynamics. This paper discusses the latest developments in using numerical analysis techniques with image data, going beyond visualization, measurement and statistical analyses.

Some of the key breakthroughs in software techniques for NDE and materials characterization include the ability to characterize properties such as permeability, porosity and elasticity, and meshing methods that ensure accurate multi-part models for design, simulation and Additive Manufacturing.Techniques have also been developed to calculate the effective material properties of scanned samples. Finite-element based homogenization can be used to calculate effective properties (elastostatic, flow, electrical…), enabling insights into material properties for scan data such as manufactured composite structures.

For non-destructive evaluation, the ability to rapidly generate 3D models from image data allows for applications such as: visualization and inspection of defects during manufacturing and design; creation of simulation-ready models for FEA/CFD solvers; and quantification of material properties and problems such as cracks in samples. This paper will demonstrate the ease by which 3D image to visualization, analysis and model generation workflows can be combined.

Introduction

There are many benefits associated with image-based modelling for non-destructive evaluation. In this context, acquiring 3D images from scanning methodologies such as CT, micro-CT and SEM provides the basis for virtual evaluation of material characteristics through accurate 3D models; these models can be exported and used for simulation applications. Using image-based techniques for design and simulation tasks in materials science, manufacturing and other fields offers an alternative and complement to CAD-based methods where idealized geometries can over-simplify analysis, particularly when inspecting samples for defects and understanding their material properties.

Software techniques have been developed at Simpleware Ltd. (Exeter, UK) that allow rapid characterization of material samples from 3D image data. As well as enabling visualization, analysis and model generation from imaging data, providing insights into material characteristics, these techniques have been extended to include effective material property calculation. Using these methods allows researchers to go further with image data when characterizing properties such as absolute permeability, conductivity and stiffness, with benefits to general non-destructive workflows.

Workflow

Image data acquisition, visualization and analysis

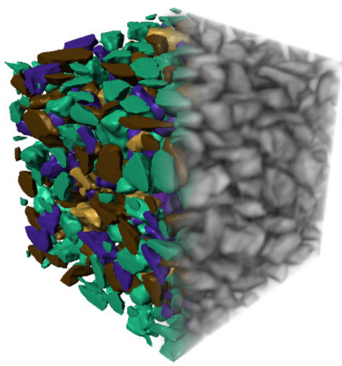

Fig. 1 Visualization of materials image data

The first step in creating accurate models from 3D image data involves acquiring a stack of images from scanning modalities such as CT or micro-CT. Images are converted from 2D pixels into 3D pixels (voxels) using image processing software. At this stage, the obtained image data can be processed to segment out regions of interest, including solid, gaseous and fluid phases. Filters can also be applied to best visualize data. Typical software techniques here include thresholding and cropping to isolate selected parts of the image data that are required for the model. Some of the benefits to carrying out these operations include being able to quickly visualize features of the image data such as cracks and other defects, as well as the ability to identify porous networks.

Comprehensive analysis can be made of material samples by using software tools to extract useful quantitative information from image data. Measurement tools can be used to better understand defects, while statistics can be obtained for properties such as pore sizes, surface areas, volume and Young's modulus. When combined with more general image processing, it is possible to combine qualitative and quantitative analysis to characterize materials with complex microstructure and multiple phases.

Mesh generation

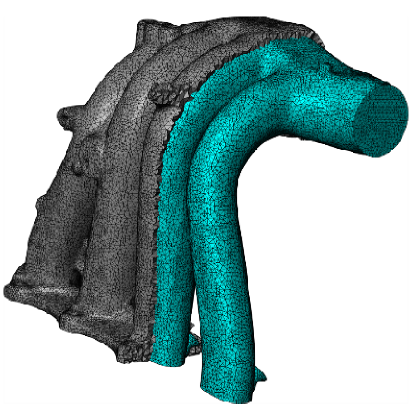

Fig. 2 Mesh of engine manifold

3D image data that has been processed and analyzed can be rapidly converted into multi-part meshes suitable for comprehensive characterization of properties, as well as for simulation applications. Image-based meshing approaches hold particular advantages over traditional CAD-based approaches, particularly in terms of reproducing complex multi-part geometries. Methods that generate accurate meshes directly from segmented image data are capable of preserving volume and topology, with the quality of an image-based mesh typically only limited by the quality of the original scans and the detail of the segmentation carried out by the user.

Software techniques developed at Simpleware include the use of an 'Enhanced Volumetric Marching Cubes' (EVoMaCs) meshing technique, which adapts the marching cubes algorithm[1] to support multiple segmentation domains. In addition, this technique, which produces very high-quality meshes, can be combined with multi-part surface remeshing [2]. With this approach, voxel-based meshes can be effectively decimated according to the size and complexity of local features. This meshing approach is particularly useful if there is a need to meet specific computational simulation requirements, and for when a mesh is very large and not practical for simulation.

With the EvoMaC approach, segmented masks are meshed to generate a mixed hexahedral and tetrahedral mesh, where voxels are converted directly to hex elements and then converted to tet elements at the interfaces to ensure a smooth surface. This surface interpolation is enhanced by taking advantage of partial volumes and by adjusting interpolation points based on voxel weighting. When used, this algorithm ensures that smoothing of images is volume and topology preserving. By comparison, when remeshing image data, target minimum and maximum edge lengths are used to decimate surfaces where possible, filling remeshed multi-part surfaces with tetrahedral elements through an advancing front technique. The advantage of this approach is that it retains the original EVoMaC surfaces, including conforming interfaces and shared nodes. These mesh generation techniques are suitable both for creating watertight surfaces for Additive Manufacturing, and for exporting Finite Element meshes for simulation tasks.

One recent example of the use of these techniques comes from research into snow deformation from X-ray tomography at the Snow and Avalanche Study Establishment, Chandigarh, India, and the Applied Mechanics Department at IIT Delhi. In this study, image data was reconstructed and meshed as finite element models using Simpleware software, before being exported for simulation of stress-strain curve of snow under deformation controlled compression. The ease by which the researchers were able to segment relevant phases from image data and generate complex meshes from microstructure demonstrates the capability of image-based meshing to achieve high-quality simulation models [3; 4].

Calculating effective material properties from material samples

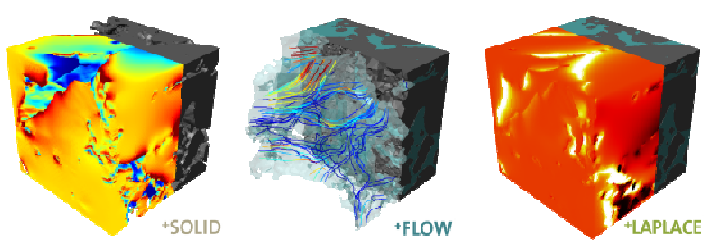

Fig 3. Calculation of effective material properties

Image-based meshing techniques can also be used for calculating effective material properties from material samples. Homogenization techniques are valuable for being able to an approximate complex heterogeneous material structure such as multi-phase composite, with a homogeneous material whose response to external loading resembles as closely that of the original material as possible. Working with materials image data can be a challenge, particularly with large datasets, and this approach can reduce time and computational demands whilst preserving a high degree of accuracy.

Traditional methods calculate effective material properties by approximating them by one of a small number of geometries whose effective properties are known analytically, for example as ensembles of spherical particles. Other methods involve deriving upper and lower bounds for the effective properties from the volume fractions (or higher-order correlation functions) and properties of individual constituent phases [4]. More recent advances in computing power and its availability to users mean that effective properties can be solved by numerically solving a family of boundary value problems imposed on a sample of the chosen material; this approach is more robust for taking into account the complex geometry of composite materials, and can solve the problem of looseness of bounds for composites with highly contrasting phases.

The methods developed at Simpleware for its Physics Modules use a built-in finite element solver to calculate the response of a cuboidal sample of a material to a specific sequence of boundary conditions associated with chosen physics; the material's effective properties are derived from the results of these simulations. A range of predefined boundary conditions are supported by the solver, covering different material sample characteristics. Results are displayed, depending on chosen physics, for uniaxial/isotropic/orthotropic approximations (with associated errors displayed as a percentage), and as a representation in both original and principal coordinate systems. The influence of boundary conditions on the final results can also be mitigated by averaging the field data over subvolumes, with graphical outputs available to check for any possible convergence of fields [5].

By using a robust and automated image-based meshing approach for multi-part segmented images, properties such as elasticity, thermal and electrical conductivity, molecular diffusivity and absolute permeability can be obtained. This 'black box' meshing approach is particularly effective in terms of avoiding the limitations of grid or voxel-based approaches with stepped surfaces that can lead to an over-estimation of the surface area between material phases. Over-estimation can have a substantial impact on the convergence and accuracy of meshes, with the FE mesh surfaces created for the Physics Modules for a given resolution being more accurate and able to converge with increasing resolution to the actual surface area of images. In addition, using adaptive remeshing tools enables meshes to be reduced in size without compromising topology and geometry, while convergence improvements can be obtained by using quadratic elements.

Conclusions

Although visualization of scan data represents a valuable way of analyzing defects and obtaining qualitative and quantitative information on materials structures, the ability to create very high-quality image-based meshes opens up potential for comprehensive non-destructive evaluation. Breakthroughs in image-based effective material property calculations are also crucial for simplifying the often difficult process of analyzing material datasets without significant computational resources. Software techniques developed by Simpleware for use in materials science applications are therefore crucial for expanding the range of options for working with multiphase image scans of composites, ceramics, alloys and other materials used for different non-destructive evaluation tasks.

References

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