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SHORT ORIGINAL PAPER

Advanced visualization for finite elements analysis in virtual reality environments

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Abstract A new visualization method for an illustrative visualization of physical parameters in immersive workspaces is presented. Through the newly developed visualization pipeline, FEM results such as stress, temperature and resulting deformation, as well as the underlying constraints can be visualized in virtual and augmented reality applications. Special features are the use of 3D glyphs for mapping stress direction and gradient as well as data preparation and the resulting data format, which was especially developed for use with VR systems. This article demonstrates the current state of VR developments, which were done at the Virtual Reality Center Production Engineering of the Institute for Machine Tools and Production Processes, for improving the analysis of complex FE datasets, and gives an outlook to future research activities.

Keywords Computer aided engineering · Tensor visualization · Finite elements analysis

1 Introduction

Simulation of physical parameters such as stresses, forces, and temperature fields on assemblies have been performed using desktop PCs ever since finite elements method (FEM) simulation software, such as ANSYS and IDEAS, emerged. These applications generate complex datasets and processed for graphic display using visualization modules. These tools provide few interactive options and often have a user interface that is designed for experts and not very intuitive. In addition, simulation files cannot easily be mixed with other files such as design review applications. The examination of component properties using a desktop PC therefore has to be performed without reference to the machine or system as a whole. Furthermore, the functionality of commercial FEM simulation programs is limited to a few standard methods, leaving the potential of innovative visualization and interaction methods largely untapped.

Aiming at improving the design process of machine tools using virtual reality (VR) systems [1,2], new visualization methods for analyzing FEM results in immersive environments were developed at the Institute for Machine Tools and Production Processes (IWP) of Chemnitz University of Technology. The major goal on the software side was visualization of the direction and gradient of stress using 3D glyphs.

In the field of scientific visualization multidimensional data is visualized in 3D-space for getting a better understanding of the underlying process. The mapping of numerical results in a 3D space ease the recognition of coherences. Usually data sets, produced out of calculations, contain different amounts of scalar, vector and tensor data. In this article the visualization of second order tensor data is attended exclusively. Higher order tensors are often be found in the field of structural mechanics for describing states of stress under the influence of external forces.

For visualizing second order tensors there have been developed several methods so far. For representing tensor in 3D space glyphs and hyperstreamlines are very suitable. Glyphs enable the representation of values at a particular point whereas hyperstreamlines [3] can visualize descriptively a continuous development of tensor data with the help of tubes and helix shapes. The main focus of this contribute builds the glyph based representation of principal stress values of the engineering mechanics whereby the use of hyperstreamlines will not be considered.

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2 State of the art

Methods and tools for visualization of FEM results in immersive work environments using VR and AR technologies were developed with the goal of optimizing consistent product and process design [4]. The VR laboratory of RWTH Aachen University, for example, enriched the VR environment with visualization methods for color-coded representation of strain fields on machinery and for overlaying the original model with the deformed grid model. Furthermore, user interaction was expanded so that the user can freely position the starting point of a force in space and control the travel paths using a haptic input device [5].

The Iowa State University in the United States created a VR application for analyzing stresses in a tractor. The resulting application does not just facilitate analysis but also lets the user modify component shapes. The user can view the stresses that exist in the machine and interactively edit critical areas, for example by deforming areas to reduce stress. The strains on the machine are shown by traditional color-coding of model nodes [6].

VISENSO GmbH offers modular visualization software for VR applications with its commercial Covise platform [7]. The basic modules can be used to visualize fluid and structural mechanical simulation results on a desktop and in immersive environments. The existing approaches to displaying FEM results in the immersive environments studied could only be used with VR systems while the study was conducted, revealing a need to develop software modules that ensure usability of both VR and AR systems. In addition, the projects examined only involve the color-coded display of comparative stress and do not include visualization of the principal stress (stress direction), which is the focus of the studies presented below.

One of the first representation forms for stress tensors is the “stress quadric” of Frederick and Chang [8]. Further glyph based methods for the illustration of principal stress states were developed from Lamé and Haber [9]. The concept of the “stress ellipse” was assigned during the foundation time of the elasticity theory between 1820 and 1830. The “stress ellipse” of Lamé is a glyph which three axes were defined from the absolute value of the highest, middle and smallest principal stress value (Sigma 1, 2 3). The ellipse is oriented according to the principal stress direction. For a more accurate representation of the stress intensity the ellipse is colored due to a defined colour scale. Hereby the warm colours (e.g., red) and brighter graduations are used for high stress values and colder colours (e.g., blue) and darker graduations stand for low stress values. For mapping the normal stress there exists methods like “Cauchys stress quadric” and “Reynold Glyphs” [10]. In the context of glyph based visualization also the method of Hashash et al. [11] has to be mentioned which uses a so called HWY-Glyph for the representation of the shear stress dimension on a certain point. To the latest development belong the “Superquadric Tensor Glyphs”, which were introduced in 2004 from Kindlmann [12]. The Superquadric Tensor Glyphs were already used in the medical field fort he representation of MRT-Tensor fields of the human brain.

In the field of structural mechanics the University of West Bohemia in Pilsen developed a vector based depiction for analyzing principal stress states at each nodes of the 3D Model in a better way [13]. The graphical representation is only suitable for a punctual analysis of the stress states with a high zoom factor. Examining a greater assembly surface stress direction and tendency can not be recognized due to the filigree line based glyphs.

3 Glyph-based representation of stress tensors

Glyphs (icons) are a way of graphically coding numeric information. A glyph is a graphic unit which can communicate various data attributes by its appearance (shape, color, orientation, position, etc.). A special characteristic of glyphs, as compared to simpler concepts, is the number of data attributes which can be communicated. Glyphs are primarily used for representing multidimensional data. There are glyph-based methods that represent a multitude of tensor values by reflecting tensor eigenvectors and values in terms of shape, size, orientation, and surface characteristic of geometrical primitives such as cubes and ellipses. A way in which glyphs can be used for graphic visualization of the stress tensor in mechanics will be described below.

3.1 Stress tensor

The stress tensor can be best explained by selecting three plane sections, each perpendicular to a direction in a Cartesian system of coordinates wherein the three forces in the sectional planes correspond to rows in the stress matrix.

$$S = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \tag{1}$$

The sketch of a very small cut-out volume element shows the assignment of the matrix content to the sectional planes (Fig. 1):

The principal stresses required to visualize stress direction can be calculated using the equation

$$\det(S - \sigma E) = 0 \tag{2}$$

where in E is the 3×3 unit matrix. Multiplying the determinant results in a third-degree equation whose solutions σ_1, σ_2, and σ_3 are the eigenvalues representing the principal stresses. They are the characteristic values of the stress matrix S. The

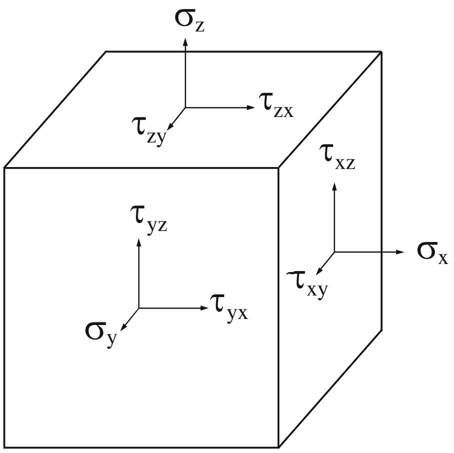

Fig. 1 Assignment of the matrix content (1) to the sectional planes

respective principal stress direction is calculated from the equation

$$(S - \sigma E)\,\breve{e} = 0 \tag{3}$$

where in the calculated principal stresses are inserted for S. The eigenvectors e1f́b-e3 represent the principal stress directions.

3.2 Reflection of stress tensors in geometrical primitives

A method based on 3D glyphs was developed from Kindlmann's studies [12], and is designed to reflect principal stress values in geometrical primitives. The extension of Kindlmann's idea is marked by the use of principal stress vectors as a coordinate system for the glyph to be created, where the principal stress intensity values determine the length of these vectors. The shape and orientation of the geometrical primitives are thus determined by three vectors (Fig. 2). Various geometrical primitives such as cuboids, tetraeders, spheres and lines can be used for reflecting multidimensional data. However, this requires a preliminary study into which shape of glyph is suitable for the data to be represented. Tests have shown that the tetraeder is very well suited for visualizing stress direction and gradient since the tip of the tetraeder indicates an exact direction. The tendency of the stress direction can be captured with a single glance compared with the depiction of main stress in the FEM-Software ANSYS (Fig. 3). In the VR-application in addition to stress direction, the 3D glyphs also reveal the type of stress (tensile/compressive stress). Starting from the model grid, the glyphs pointing outwards indicate tensile stress and the bodies pointing inwards indicate compressive stress. Another advantage is topology due to which the glyph shape requires little geometry and the application clearly performs better, compared with cuboids. A change in the form of representation should be adjusted to the respective job (analysis of the stress gradient, comparison of the principal stresses, etc.). During analysis in the VR environment the user can interactively define which form of glyph to use for representing principal stresses (Fig. 4).

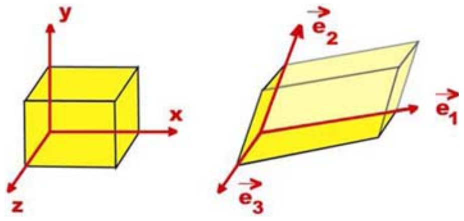

Fig. 2 Principal stress vectors form the coordinate system

4 Representation in virtual environments

The data has to be brought into a specific structure to show the results in the VR visualization software. A data reading routine was implemented that creates a data container for each node. Each node is thus assigned a data object which contains the associated scalar, vector, and tensor values. The reader module reads ASCII and binary-coded files and processes the linear elements (tetrahedrons with four nodes) and parabolic elements (tetrahedrons with ten nodes) these files

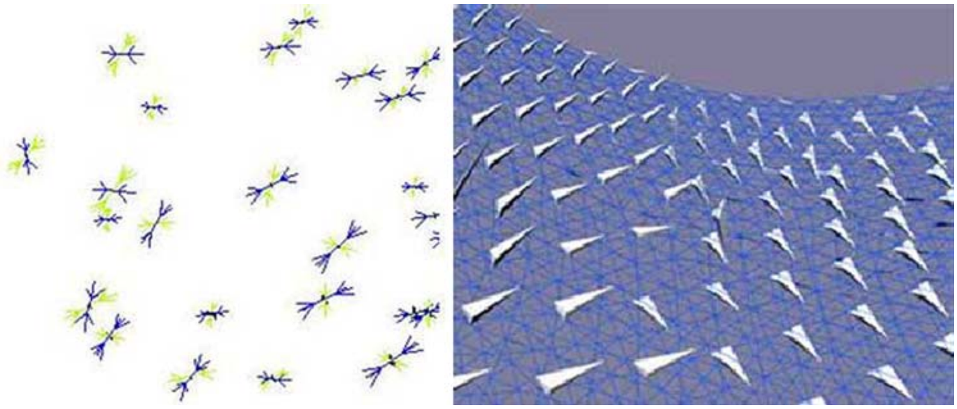

Fig. 3 Visualizing tensile/compressive stress in ANSYS (*left*) and in the VR-application (*right*)

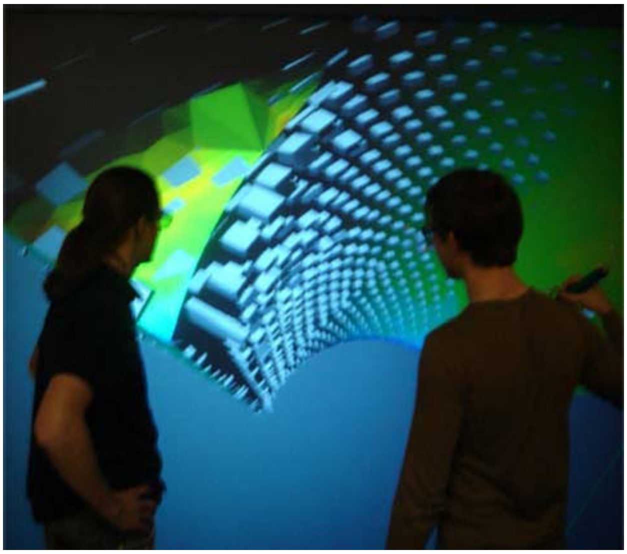

Fig. 4 VR-based FEM analysis of an assembly (stress direction display using cuboid shaped glyphs)

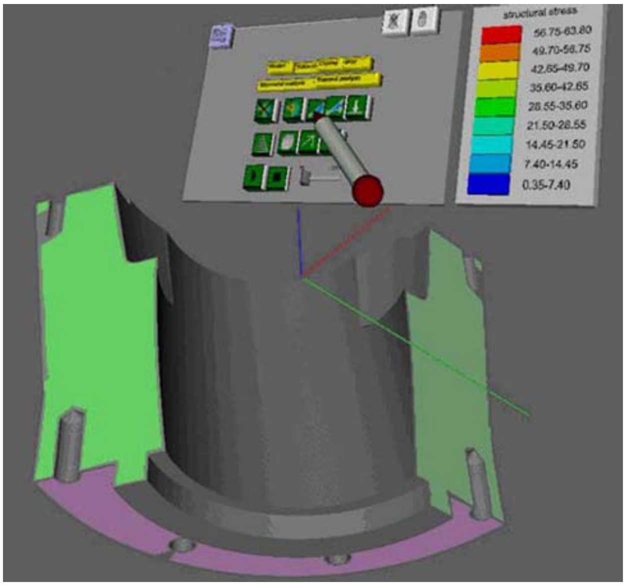

Fig. 5 Boundary conditions "Constraints"

contain. Since the use of parabolic elements in the FEM software results in a more precise calculation of property values (from experience the authors can say that the comparative stress according to Mises is 1.5–2 times greater with parabolic elements than with linear elements), these values should be represented accurately in the VR visualization. Therefore an import function for the parabolic element type was implemented in addition to the data reader module for linear elements. Furthermore, filter modules for creating the grid surface and for placing sectional planes were developed for each element. Mapper modules represent physical variables at a certain point in the three-dimensional space. Specific values are represented graphically by assigning colors or generating geometrical shapes and their properties. The mapping modules required were specifically designed for visualization in VR environments. The data format used, which separates the geometrical information from the FEM result values, enables fast display of selected data.

A power wall with stereoscopic projection was used as an output system to evaluate the modules designed in a VR environment. The designed VR demonstrator enables the display of the calculated properties from structural mechanics (Fig. 4) and underlying boundary conditions (Fig. 5) as well as thermodynamics.

The demonstrator was developed with the VR/AR-software Studier Stube [14] a client-server architecture in which the server is responsible for reading the data, generating the grid, and for calculations. The Studier Stube application functions as VR client which performs the rendering and interactive functions. There is a bidirectional communication layer between server and client.

The object of the demonstrator is a chuck which is used in a drill press co-designed by IWP. The physical prototype for this project is available in a test building at IWP. The physical prototype of the chuck was optimized with regard to weight/mass (structural analysis). A topology optimization aimed at saving material was performed as part of a graduation paper project. The chuck was to become more lightweight but retain its stiffness. Furthermore, the heating up of components was simulated to localize critical temperature fields and study their impact on deformation of the component (thermal analysis). The component properties calculated using the ANSYS software were used in the demonstrators described here.

The success of a VR application depends on the quality of the user interface. It should be designed so that it allows fast access to the required data. Intuitive controls are a prerequisite. Icons are to be used wherever possible since capturing an image is faster than reading labels. The number of navigational planes used should be easy to grasp. The user interface required to control the FEM analysis was implemented using the Studier Stube interactive concept. The basic components available (virtual tablet with controls and input pen) have been modified according to application (Fig. 6). Use of a physical tablet with an overlay by virtual controls proved to be too heavy in longer sessions and required recalibration for each session and thus an extra effort. It was perceived to be more convenient to operate the controls on the virtual tablet placed relative to the head position in the VR scene, which is why this design was chosen.

5 Conclusion

The newly developed VR-based methods allow the study of component characteristics in the machine environment and

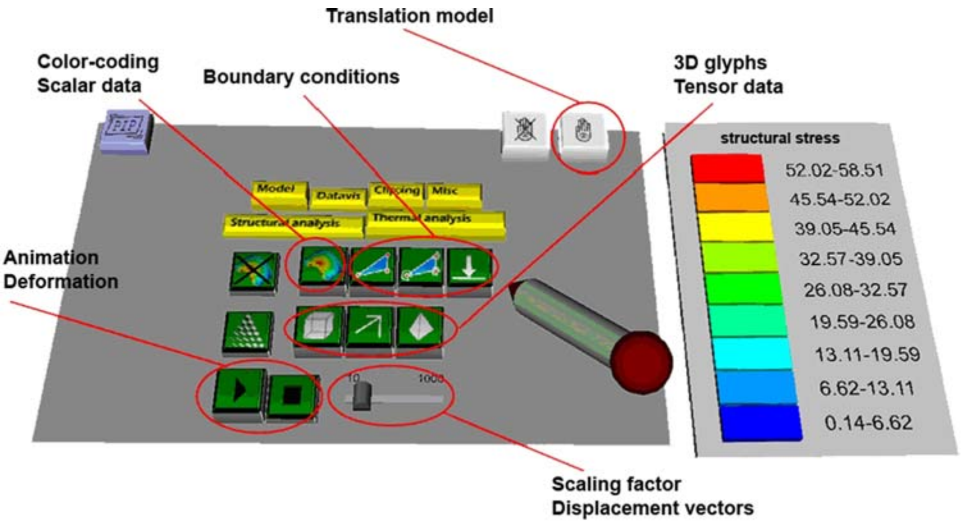

Fig. 6 User interface for controlling the FEM analysis

the merger of results from structural and thermal analyses into one application, which results in a more efficient and informative process of analysis. Use of stereoscopic visualization methods and glyph-based display support human perception and improve comprehension of complex data. The VR-based interactive options in six degrees of freedom enabled direct access to specific portions of a dataset.

The result of this research differs from previously designed methods of VR analysis of FEM findings in its glyph-based display of stress direction and type. Hereby the use of Eigenvectors as coordinate system for generating the glyphs defines a new way for visualizing the direction, tendency and type of principal stress in the field of structural mechanics. Another unique feature is interactive scaling of displacement vectors, which makes component deformation visible through scaling levels of different size. Another innovative feature is the provision of both structural and thermal analysis findings in one application enabling, for example, direct comparison of the impact of force action and heat on the component shape. Yet another special feature is data preparation and the resulting data format which also allows visualization on mobile AR systems.

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