Recent Developments in Isogeometric Analysis for LS-DYNA®

David Benson
Attila Nagy
Liping Li
LSTC, Livermore, CA, USA

Stefan Hartmann
Dynamore GmbH, Stuttgart, Germany

Abstract

Isogeometric analysis (IGA) uses the spline functions from CAD (computer-aided design) for analysis with the objectives of 1) reducing the effort of moving from design to analysis, 2) using the actual geometry of the parts from CAD instead of approximating them with polynomials, and 3) obtaining higher order accuracy through the higher order basis functions of CAD. LS-DYNA is the first commercial code to support IGA through the implementation of generalized elements, and then through key word descriptions of patches of B-spline and NURBS elements. Three shell formulations and a solid element formulation are currently available. Additional recently added capabilities, including improved contact, anisotropic material modeling, spotweld models and support for unstructured spline capabilities through the specification of their Bezier extractions. These and other recent additions are described and demonstrated. In addition, some of the difficulties industry has encountered in moving to this new technology are discussed.

Introduction to Isogeometric Analysis

NURBS are the most commonly used functions in computer aided design (CAD) for representing the geometry of the boundaries of parts. They are popular because they can represent basic geometric shapes exactly with only a small amount of data, while also being able to define very general shapes that are not amendable to being described by simple analytical functions, e.g., car bodies. NURBS are defined on rectangular patches. To represent more general shapes, trimmed NURBS are defined by deleting parts of the patches specified by trimming curves.

Isogeometric analysis [1] was introduced in 2005 by Thomas J. R. Hughes and his students, Austin Cottrell and Yuri Bazilevs. Its objective was succinctly summarized in the abstract: “Basis functions generated from NURBS (Non-Uniform Rational B-Splines) are employed to construct an exact geometric model. For purposes of analysis, the basis is refined and/or its order elevated without changing the geometry or its parameterization.”

Isogeometric analysis was originally tested in LS-DYNA through the generalized element formulation introduced and implemented in the code by D. Benson while on sabbatical at the University of Texas, Austin with Tom Hughes in 2007. During the next few years, they were added as part of the standard element library by the current development team of D. Benson, S. Hartmann, A. Nagy, and L. Li.

This paper summarizes some of the recent additions made to the IGA capability in LS-DYNA that we believe will be of the greatest interest to the user community. The details of these additions are provided in separate papers.

The Importance of Geometry

The primary motivation behind isogeometric analysis is the use of the exact geometry for the analysis. The two attributes of NURBS in CAD that provide the geometric flexibility are 1) using them to define the boundary representation and 2) trimming them to arbitrary shapes. Unfortunately, they introduce obstacles to the use of NURBS in analysis.

The difficulty of using boundary representations (B-rep) for analysis is the absence of any basis functions on the interior of a solid object for representing the displacement field. This difficulty can be overcome by using boundary element methods (BEM), but that limits the solutions to linear problems. Trimmed NURBS surfaces have their own problems. Their arbitrary shape means that special integration rules need to be formulated for each trimmed element. Stability can also be a problem. By far, the biggest difficulty with them is joining the edges of trimmed boundaries together since their basis functions don't line up like for untrimmed NURBS patches and standard finite element formulations.

The CAD software packages introduce their own set of challenges. At the time that these packages were being developed, no thought was given to the possibility of using the NURBS patches in the future for analysis. Ideally, each part would be represented by a minimal number of patches to maximize the smoothness of the geometric description and the convergence rate of the analysis. However, CAD models are revised over and over again during their lifetime, with the result that patches proliferate and minute gaps in the geometry are filled in with patches that are little more than slivers. These issues not only have a negative effect on analysis, but also on other uses of CAD geometry such as 3-D printing and importing CAD models from one CAD program to another. As a result, there is an entire industry devoted to "healing" CAD models with products such as Elysium's CADdoctor.

The process of generating a mesh from a CAD model is referred to as "mesh generation" and in IGA, it is referred to as "creating an analysis suitable geometry" (ASG). Many of the basis functions used in the ASG are not commonly used in CAD. Since CAD defines solids in terms of two-dimensional boundary representations, even the simplest three-dimensional NURBS function is not found in CAD models. Some of these basis functions allow local refinement of the computational mesh and relatively unstructured meshes in comparison to NURBS. This is a very active area of research in the mathematics and engineering communities.

New Capabilities

One of the challenges associated with IGA is maintaining the continuity of the solution around extraordinary points. In two dimensions, extraordinary points are interior control points/nodes that are connected to something other than four nodes. A simple example of an extraordinary point can be constructed by using three rhomboid NURBS patches to construct a triangular domain. The common control point where the three patches meet is an extraordinary point. In CAD, it is possible to adjust the locations of the control points for the particular geometry so that a surface maintains its higher-order *geometric* continuity. For analysis, however, continuity of *the basis functions* must be maintained for arbitrary deformations of the mesh, which is much more difficult.

Addressing the extraordinary point challenge is one of the most active areas of research in IGA. Many new and different spline formulations have been proposed, and it is likely that many more will be introduced before the CAD industry settles on a few standard treatments. Each of these new spline formulations has its own terminology, data structure, and unique properties that make expressing them in terms of the current NURBS patch input formats impossible.

To help researchers test their ideas for creating analysis suitable geometry, LSTC is now supporting the so-called "BEXT format" informally through *INCLUDE_TRANSFORM. "BEXT" stands for "Bezier extraction", the set of constants for each element that define the linear transformation from Bezier functions to the spline formulation. This set of constants defines a matrix that has as many rows and columns as the element has basis functions. For example, for a solid element using cubic splines, there are 64 nodes, and the Bezier extraction matrix contains 64 x 64 = 4096 entries. Even in two dimensions, cubic splines would require 16 x 16 = 256 entries for each shell element. This is clearly not a practical format for automobile crashworthiness applications.

The possibilities of the new spline technologies being proposed are very exciting (see Figure 1). We believe that future, internationally-supported, open formats, such as the STEP format, will provide the means of including these splines into production analysis in the future.

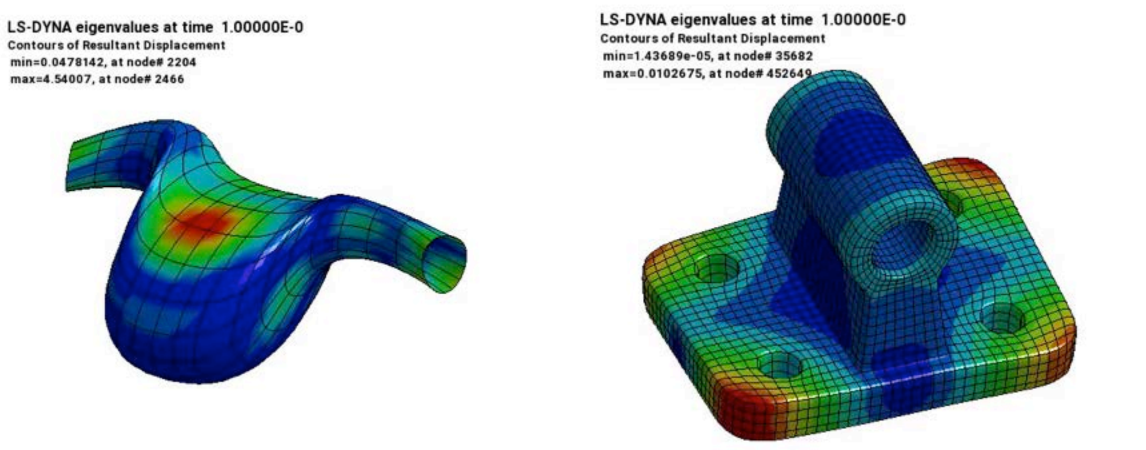

Figure 1: A shell element BEXT model from Coreform on the left is shown with a three-dimensional solid element model from the research group of Professor Jessica Zhang at Carnegie Mellon is shown on the right.

The one-step analysis for metal stamping now supports IGA. No additional input is required from the user for this capability with IGA. The output is written to igaonestepresult and it may be used in exactly the same manner as the standard dynain file. A comparison of the initialization of a FEA and an IGA model is shown in Figure 2.

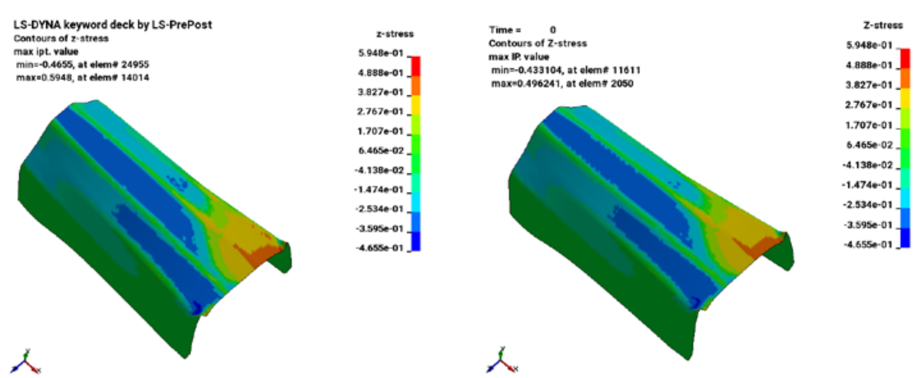

Figure 2: The one-step solutions using finite elements (left) and trimmed NURBS (right).

Recent Enhancements

Our long term goal is to provide all of the same functionality for IGA that is available for the standard FEA in LS-DYNA. This requires numerous small changes as both the capabilities of IGA and FEA expand.

We have recently enhanced the trimmed NURBS definitions with *DEFINE_NURBS_CURVE. This permits trimmed NURBS that exactly match the CAD trimmed NURBS definitions. In previous versions of the trimmed NURBS, LS-DYNA relied on the standard *DEFINE_CURVE that is limited to linear interpolation between points. This compromised the accuracy of the trimming curve unless a large number of points were used.

Numerous enhancements have also been made to the boundary conditions to support prescribed motion, spotwelds, and pointed, distributed, and prescribed pressure loads. See the documentation for *CONSTRAINED_NODE_TO_NURBS_PATCH_SET and *LOAD_NURBS_SHELL_ID for additional details.

Consistency and performance has been improved in the SMP, MPP, and hybrid versions.

The stable time step size estimate has been improved for trimmed and untrimmed elements.

Section forces for shells and solids are now supported for post-processing.

The majority of anisotropic material models are now supported for IGA elements.

The algorithm for mapping the solution from the IGA elements to the interpolation elements used by LSPP for graphical display has been improved.

Future Developments and Challenges

Our highest priority is working with the CAD and CAE vendors and researchers to develop the tools necessary for generating IGA models for the existing capabilities within LS-DYNA. We recognize that this remains the biggest obstacle to using IGA in industry. Post-processing the results is nearly as important and we will continue to work on it.

In terms of analysis, we are working to make the capabilities that are most important to users of FEA also available within IGA. This includes everything from basic boundary conditions to coupling to the various other physics solvers.

Contact is still handled primarily through the interpolation elements and it is currently not available for implicit. We hope to change this in the upcoming year.