COMPUTER-AIDED DESIGN & APPLICATIONS, 2016
VOL. 13, NO. 2, 208–220
http://dx.doi.org/10.1080/16864360.2015.1084190

CAD/CAE associative features for cyclic fluid control effect modeling

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ABSTRACT

Nowadays, CAE has been widely applied in industry as an auxiliary tool for decision making. However, human intervention still is required in reasoning CAE results and in determining design change effect. Ideally, CAD and CAE should be seamlessly integrated where design changes, effect analysis and function reasoning should be explicitly supported by automatic feature extraction in a cyclic manner. This paper presents two CAD/CAE associative feature concepts, which form a robust mechanism aiming to support automatic CAD/CAE interactions with both geometric and semantic information. Firstly, a concept of *CAE boundary feature* is proposed to model and record the simulation intents, and therefore, the CAE analysis cycles could be managed with the consistent initialization setups, e.g. boundary conditions, mesh types, and physical models. Secondly, CAE results are processed by extracting the differential characteristic features, which are named as *CAE effect features*. An effective feature reflects the sensitivity information related to each engineering change and hence leads to the evaluation of design modifications. Consequently, the cyclic design modifications can be tracked and reasoned; then further modifications are guided to converge into the optimum. The research innovation lies in the proposed CAD/CAE integration scheme which has been explored preliminarily to demonstrate an automated and efficient way to keep the CAD/CAE semantic consistency over cycles of optimization. A case study about hydraulic valve development is presented.

KEYWORDS

CAD/CAE associative feature; CAE boundary feature; CAE effect feature; design automation; CAD/CAE integration

1. Introduction

CAD/CAE integration remains to be a demanding research topic in the past two decades, as interfacing simulation and design tools for intelligent product development is still widely recognized as a technical gap without a general solution. Although a number of approaches have been studied, seamless CAD/CAE integration has not been fully realized. The majority of efforts focused on the front process of preparing the CAD model for CAE analysis effectively and efficiently. The close loop CAD/CAE interactions remain to be a research issue, and there are mainly two difficulties: how to synchronize the CAD and CAE models and how to interpret CAE results for design modification evaluation. In order to overcome these difficulties, this paper presents two new concepts. For the former difficulty, a *CAE boundary feature* concept is proposed to manage the geometric and semantic associations between CAD and CAE models based on the well-established associative feature concept [17]. This CAE boundary feature is defined as a software object class and its application is put forward as a robust tool to maintain analysis setup information consistency during the cyclic CAD/CAE mesh information conversion. For the latter difficulty, another class, referred to as *CAE effect feature*, is introduced by extracting the sensitivity information from two consecutive CAE run results; such extracted information are necessary for identifying proper design modification direction. By introducing these concepts, a new CAD/CAE integration framework has been developed which covers both the forward and reverse integrations and supports more automated cyclic product development. Before getting into the details, a brief literature review about CAD/CAE integration is presented below.

From early 1980 s to 2000, CAD and CAE researchers focused on the geometry conversion and simplification. During that period, semantic information related to the CAE geometry meshes was missed during the conversion, and redundant efforts were needed to recover the lost information, i.e. the boundary conditions. Therefore, the efficiency is low, especially for cyclic design processes.

To make up this deficiency, there are two common approaches proposed: one is to develop an integrated

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system with both CAD and CAE modules, for which the feature-based techniques are supposed to maintain the semantic information during model conversion; the other is to develop a unified feature model incorporated with both CAD and CAE information, with which both CAD and CAE views could be extracted and the information consistency could be easily sustained [2].

For the first approach, Kao *et al.* [13] introduce an integrated system to generate thread rolling die-plate geometry. The design parameters are linked to SolidWorks through Microsoft Excel. Matin *et al.* [19] put forward a feature-based CAD/CAE integration system for mold design. With the commercial CAD software Pro/Engineer, the specific mold design module guarantees rapid mold modification. The simulation module determines the injection molding parameters. Lin and Kuo [15] build an integrated CAD/CAE/CAM system for automobile stamping die development. In this system, STRIM is used as 3D surface construction CAD software, CATIA as CAD/CAE software, DYNAFORM as stamping formability analysis software and CADCEUS as CAM software. Johansson [12] develops a prototype system to integrate SolidWorks, ANSA and LS-Dyna simulating the behavior of ski-racks during car collision. For the latter, Deng *et al.* [5] propose the CAD/CAE feature concept to incorporate both CAD and CAE design information. CAD/CAE features are related to both design and analysis processes. Geometric information from CAD features is assigned to CAD/CAE features. The design intent derived from analysis constitutes the CAE portion of the CAD/CAE features. The integration can be established once all the CAD/CAE features are created. Lee [14] develops a feature-based single model for CAD and CAE integration. It is unique for the multi-resolution and multi-abstraction modeling techniques making it capable for a wide range of applications. Cuilliere and Francois [4] establish a unified topological model to integrate CAD, FEA and topology optimization. This originally developed environment and database organization enables multi-source model utilization, automatic meshing, reanalysis corresponding to remeshing, and topology optimization.

CAE analysis is carried out to check whether the design is satisfactory. If not, reasoning of the analysis result is significant in guiding the following design modifications. This actually forms the reverse process of CAD/CAE integration. Different methods are available to properly interpret the analysis result. Merkel and Schumacher [20] utilize response surface methods in the CAE driven product development. Park and Dang [21] use commercial CAD and CAE software constructing an integrated system to achieve structural optimization with metamodeling techniques including response surface method and radial basis function. Robinson *et al.* [22] propose a method to obtain optimized design by adding new parameters or features to CAD model incrementally.

For cyclic CAD/CAE integrated design process, CAD/CAE model synchronization is also important. For this purpose, the associative feature concept proposed by Ma and Tong [17] is the right mechanism to realize the seamless synchronization. An associative feature is defined as a set of semantic relationships which can be both geometric and non-geometric among different geometries or applications. Associative feature is a new concept which distinguished from traditional form features [18]. Associative feature can not only manage fixed relations but also the developing ones which are derived from them. Features which are based on volume of material are just specific types of associative features. More importantly, different from form features, associative features can be independent of volume. This is the key characteristic explaining the reason why associative features can also reveal and manage the relations embedded in the application system.

There have been commercial software tools providing integration support. For example, SolidWorks has a Computational Fluid Dynamics (CFD) module embedded in the software environment. ANSYS Workbench is capable to carry out modeling, meshing, simulation and optimization in a single environment. TOSCA is integrated in this environment as the optimization module [1]. It has a wide range of application in solid and fluid mechanics. The optimization result is remeshed automatically to get validated. However, the CFD module in SolidWorks is not comprehensive due to its limitation in mesh type and solver. The usability of the modeller in ANSYS Workbench is not sufficiently powerful and flexible. Moreover, the optimization process is not fully automated. In these commercial and integrated packages, high-level feature information is still not explicitly managed in the CAD/CAE interaction conversion cycles [25]. In general, there are some limitations both in the research and application of CAD/CAE integration. CAE-oriented design information cannot be fully described. The CAE calculation accuracy which has not obtained enough emphasis is actually a critical factor in the formation of integration. In addition, few researches are conducted in the fluid domain. As a result, further research on this issue is needed.

The rest of this paper is organized as follows. The new feature concepts are introduced in Section 2 to facilitate the CAD/CAE integration. Based on the features brought forward, Section 3 explains the mechanism how CAD and CAE integrate in detail. A case study of hydraulic valve is illustrated in Section 4 to show the effectiveness of this method. At last, conclusions towards the presented work are made.

2. Feature concepts in CAD/CAE integration

As mentioned earlier, associative feature is capable of establishing and managing both geometric and non-geometric associations. Therefore, associative feature concept is used in this work to interface the CAD and CAE tools, which synchronizes the different application models and guarantees the data consistency. The overall integration scheme is shown in Fig. 1.

The design flow starts from the conceptual design which preliminarily satisfies the design requirements. Given the optimality, the conceptual design is still immature and requires the simulation-based design modifications. The conceptual design model conveys both geometric and non-geometric information; therefore, it is significant to guarantee the complete information transfer between CAD and CAE tools. The CAD/CAE *associative feature* plays the roles in fulfilling this seamless integration. To be specific, all geometric entities from the CAD model and analysis model employ the one-to-one correspondence, and the semantic information useful for CAE analysis is also linked to analysis model. In this way, the CAE analysis setup could be automatically completed without redundant model preparations.

The accuracy of calculation is critical in the cyclic CAD/CAE integration because the analysis depends on the previous calculation. Proper application of boundary conditions is very important to obtain accurate result, because they will not only affect the type of mesh generated but also the setup of the solver. Many research works are dedicated in the integration of CAD and CAE, but rarely focus on the accuracy. However, if the result is not valid, the integration would be meaningless. As a result, the CAE *boundary feature* is proposed to manage the relations among the geometry, boundary conditions and specific mesh type. Fig. 2 shows the semantic associations in this CAD/CAE integration process. Based on the associative feature concept [17], CAE boundary feature can be defined as a class of features that contains the mapping relations of geometrical dependencies between CAD entities and their associated CAE mesh representations, e.g. grids and tetrahedrons, as well as non-geometrical dependencies, such as inherited properties, like fluid properties, fluid space body face names, tags, constitutional structures, and conceptual constraints to apply CAE boundary conditions. For example, in computational fluid dynamics, the velocity and pressure boundary are assigned to the inlet or outlet of the geometry according to the application situation. The walls formed by the faces of the fluid body geometry are subject to no-slip boundary condition. Particularly, mesh inflation should be applied along solid walls to pursue higher accuracy because it is capable of estimating the steep gradients in the boundary layer.

Generally, if the number of the meshes is increased, the computational cost will be higher accordingly. Here in our presented approach, the accuracy is not achieved by the number of the meshes, but the type of meshes. As we used Fluent^{TM}, mesh inflation is applied along the wall boundary in order to obtain more accurate result. As a result, this approach can achieve higher accuracy without

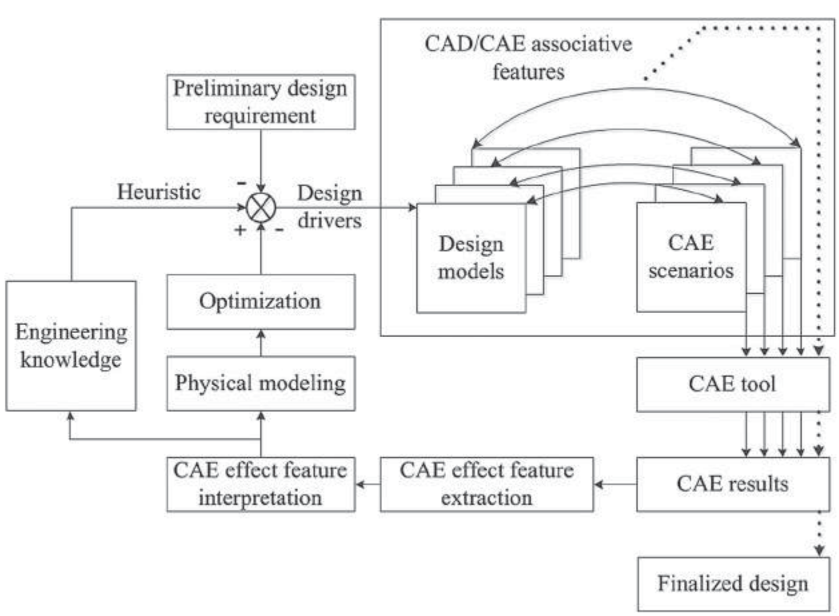


Figure 1. CAD/CAE Integration Scheme.

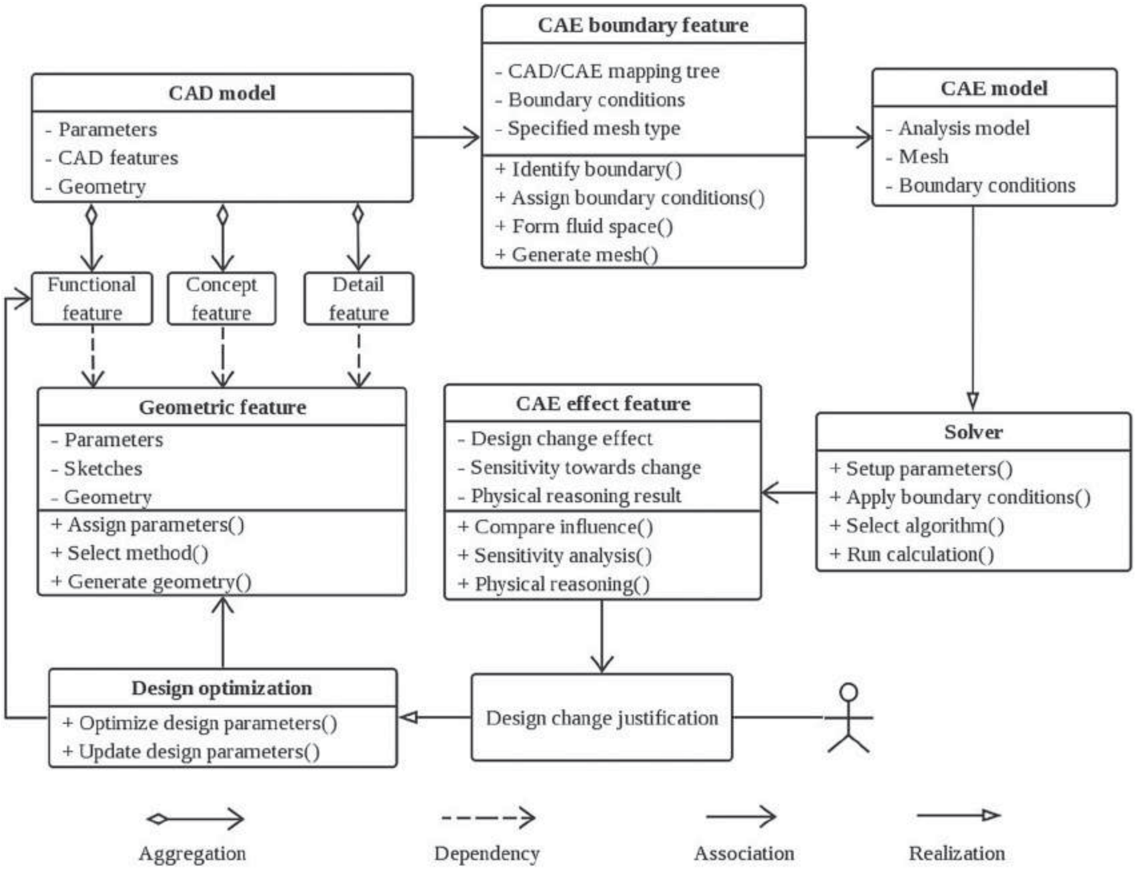


Figure 2. Semantic Associations in CAD/CAE Integration.

reducing computational speed. This is because of the use of inflation mesh type, which is well-supported by the CAE boundary feature which maintains the consistency during iterations. The reason why we address the importance of accuracy is that the optimal design will not be achieved without rounds of accurate iterations. The proposed approach provides an efficient way to increase and maintain the CAE accuracy.

Smit and Bronsvoort [23] suggested an analysis view which is an interface concept to interact with mesh generation, boundary conditions, analysis model, and solution methods in a multi-view feature modeling environment. In the proposed approach, CAD model and CAE model are associated through the CAE boundary feature. In comparison, the CAE boundary feature expands its associations to the design model and the following optimization process in the integration loop. It is a robust tool to maintain information consistency during the iterations.

Currently, human intervention in the CAE analysis still plays an important role in decision making. To obtain a better design, specialist will usually make the decision on the modification and then process the change. This is a tedious process because the CAD model may be modified for hundreds of times and CAE analysis should be conducted accordingly. In order to realize automatic interpretation of the CAE result, the concept of CAE effect feature is proposed here.

As shown in Fig. 2, CAE effect feature is also defined as a class of features that represents the unique characteristics of interested measure changes for a physical behavior in the context of a CAE analysis scope; in other words, its applied instances explicitly express the influence on the physical performance of a defined function due to the incremental concept changes in the associated CAD model. This concept is of significant importance to form the loop of CAD/CAE integration. After the analysis of the initial design, the system will attempt a method for the modification of design parameters. Then, the CAD model and CAE scenario will be updated synchronously, resulting in new CAE analysis results. CAE effect features will be extracted from the difference between the new analysis results and the previous ones. This cyclic process will be conducted in an iterative way. As a result, more CAE results will be obtained from different design models and corresponding CAE scenarios, which contribute to find the trend of design propagation. With the set of CAE effect features extracted, the interpretation can be carried out and the optimized design would be possibly achieved with the help of physical modeling. In addition, it should be noticed that engineers can still intervene the system after the CAE effect features extraction. Based on engineering knowledge, they can check whether the modification is promising and determine the next step of modification.

In summary, Fig. 2 expresses the functions of CAE boundary feature and CAE effect feature properties explicitly. Therefore, the changes in CAD design can be reflected in CAE scenarios accurately. CAE effect feature is a powerful tool to manage the effect caused by different design regardless of the modification sequence. CAE effect feature has a flexible data structure making it capable to realize decision making. Engineers can interpose the justification based on their knowledge. By optimization method, design parameters will be updated until an optimal design is obtained. Meanwhile, all the features of the design model can be updated synchronously. The formation of this loop is the foundation for CAE effect feature extraction and design optimization.

3. Integration of CAD and CAE

The mechanism of CAD/CAE integration is to be introduced in this section based on the background of fluid dynamic analysis. Because the hydraulic system is highly standardized, the components such as control valves and pumps can be modeled by feature-based and parametric approach. Parametric modeling can be easily achieved by the built-in expression function library in a CAD package like SolidWorks™ and NX™. By introducing appropriate constraints, a parametric model can be constructed in such a way it can be readily integrated with automated optimization loops [6].

Fluid space is abstracted from the established geometry by Boolean operations. Because face IDs in CAD system may differ from that in another system [24], the IDs of fluid space faces will be assigned specific tags with attributions and boundary conditions attached. The tag is an identifier which can be recognized by both CAD and CAE systems. It works as part of the CAE interface protocol. The information of entities with tags is stored in database for later processes. Tab. 1 shows the mechanism how the information is transmitted between different modules, in which m, n, p and q are the numbers of corresponding faces in CAD model.

Table 1. Information Transmission in CAD/CAE Conversion.

Tag	Attribute	Boundary condition
$I_1, I_2, \ldots \ldots, I_m$	Inlet	Velocity or pressure inlet
$O_1, O_2, \ldots \ldots, O_n$	Outlet	Velocity or pressure outlet
$W_1, W_2, \ldots \ldots, W_p$	Wall	No-slip wall
$S_1, S_2, \ldots \ldots, S_q$	Symmetrical plane	Symmetry

Based on the design of a control valve, Fig. 3 shows the detailed CAD/CAE integration mechanism. The valve can be parameterized by the dimensions in both axial and radial direction. The diameter of the valve core determines the scale of the fluid space formed by the valve core outer face, valve sleeve face and valve body inner face. Meanwhile, according to empirical formula, valve core diameter is decided by many factors. Such kind of information forms forward physical reasoning, which will be useful in the optimization process. The majority of fluid space faces are subject to the no-slip boundary condition which is defined as walls. In order to reduce the computation load, only half of the model is calculated due to the symmetric property of geometry. Not all of the CAE features are geometrical features, such as the parameters of the hydraulic oil and the value and type of boundary conditions.

After all the parameters defined and geometry established, CAE boundary features will be established to link geometry characteristic faces of the fluid body, meshes, corresponding boundary conditions and the specific mesh generation method. The fluid body geometric faces such as inlets, outlets, walls and symmetrical planes with unique tags will be indexed from the database and assigned names with the type of boundary. Later in meshing stage, CAE boundary features also direct the mesh generation and refinement. For example, mesh inflation is applied along the wall boundary in order to obtain more accurate result. CAE Solver invoked by the CAE module will automatically recognize the boundary with such kind of names and the assigned boundary conditions correspondingly if applicable. As a result, after the CAD model is updated, the CAE model, including both geometric and non-geometric information, can be synchronized accordingly. In this process, the non-geometrical parameters remain unchanged. CAD/CAE feature information sharing is achieved by the associations embedded within the CAE boundary feature.

After the mapping from CAD module to CAE module, the meshing of fluid space should be conducted. This is a key process in this cycle because it will highly affect the accuracy of result which is a critical factor in the integration. Some detailed features may greatly increase the time required for meshing and Finite Element Analysis (FEA). Even, they may lead to the failure in mesh generation [26], which will end up the whole process. It is important to remove the irrelevant geometric details within the error limit providing precondition for steady calculation. Estimating the effects of removing negative features in engineering analysis can be achieved [16]. Ferrandes *et al.* [8] put forward a method not only evaluate the error of simplification but also repair the model if the simplification triggers unacceptable error. Simplification

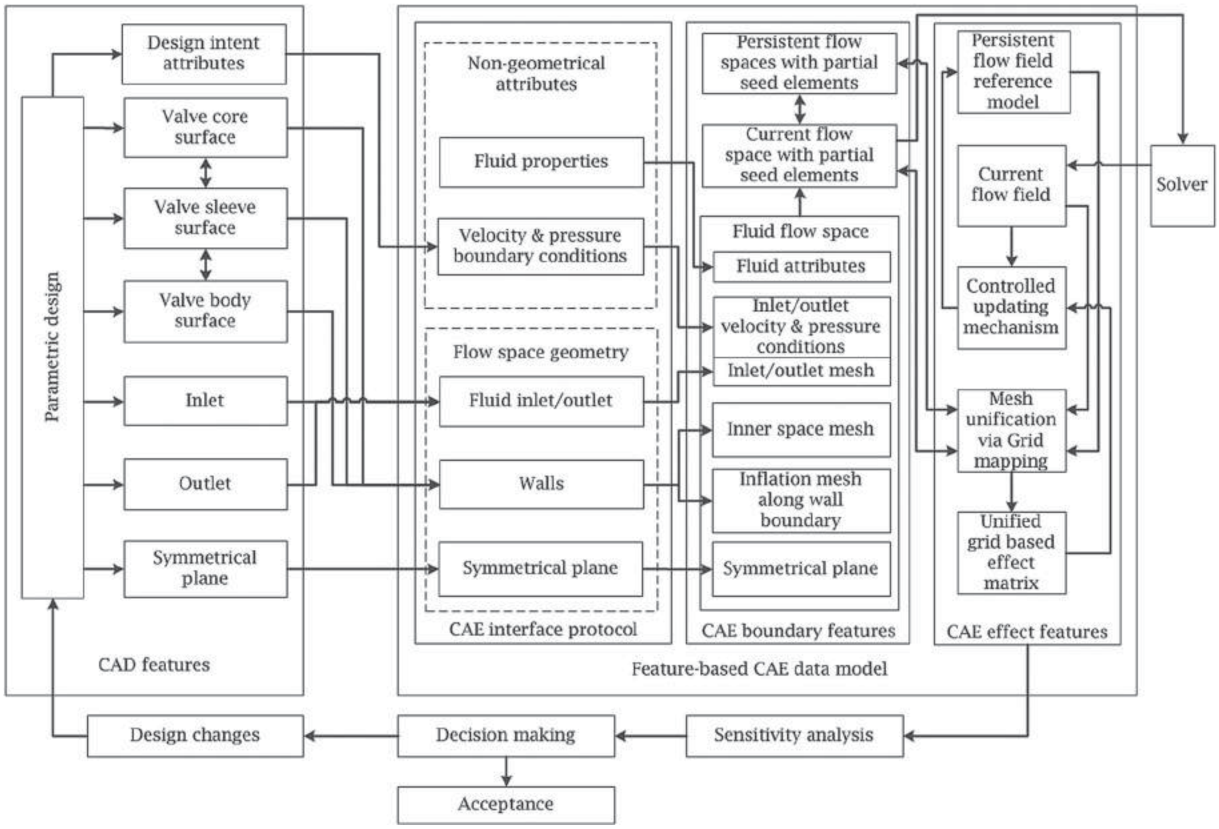


Figure 3. CAD/CAE Integration Mechanism.

features concept [11] was proposed to identify the details to be simplified and maintain consistency between CAD model and FEA model. The assessment and control of simplification will increase the robustness, accuracy and efficiency in cyclic integration.

Under the control of CAE boundary feature, the fluid flow space is meshed. Each of the CAE mesh cell associated with the local fluid attributes, is modeled as an object; the data type, such as the generic data structure of a mesh element associated with the local fluid flow properties, is defined as an object class, named as a *partial seed element* in this proposed framework. The entire flow space with partial seed elements is processed by FEA in the solver. Finite Volume Method (FVM) is applied because it is usually the most efficient for flow simulations comparing to Finite Difference Method (FDM) and Finite Element Method (FEM). The analysis results are checked to see whether any of the constraints in the design requirements is violated. Optimization will be needed if the original design does not meet the requirement. Both of the CAD and CAE features will be modified after the modification of the design parameters, such as the valve core diameter. The change of design parameters will be reflected on the fluid space directly due to the associations. Subsequently, the remeshing of fluid space will be carried out. The introduction of CAE boundary feature is useful for the cyclic analysis setup because it enables consistent reassignment of boundary conditions to the mesh geometry automatically in each iteration after remeshing. For the model which remains unchanged, adaptive remeshing strategies [10] are used in CFD to control the error level on given numerical solution by updating mesh according to the error estimator. For modified model, using the prior existing meshes, efficient remeshing can be done [27]. This approach provides a robust way to regenerate the mesh after geometry modification. A 3D automatic remeshing method [9] is well suited for remeshing models with small design parameters change.

To facilitate the measurement of flow field comparison before and after an incremental change of design, the states of the consecutive flow fields have to be "memorized." The state of flow field before an interested design change is introduced and stored as a reference state with a mesh space associated with a matrix of flow properties. This reference flow state is called persistent flow space with partial seed elements (PFSPSE). Then the new simulated results, which are reflected by the new state of flow field with another associated mesh space, is named as current flow space with partial seed elements (CFSPSE). Ideally, these two states are comparable automatically, because by updating the PFSPSE with the input of CFSPSE, cyclic CAD design change effect could be consistently represented. PFSPSE can also be understood as the pre-defined reference state, while CFSPSE is generated according to the current design through the actions of solver in each design iteration.

Theoretically, by working out the difference between PFSPSE and the updated CFSPSE, physical sensitivity analysis could be carried out further, which potentially provides the direction of design changes after the necessary human or artificial intelligent evaluation. Hence the authors define the concept of CAE effect features, which are the CAE flow field differences of different rounds of analysis results; they will reveal the sensitivity towards design changes. This will provide the backward physical reasoning. Hence, by reasoning of a physical phenomenon, engineers can figure out the method of modification and thus make progress for design optimization iteration by iteration.

It can be appreciated that the extraction of CAE effect feature needs comparable mesh grid distributions between the two checking simulated flow fields. However, the mesh grids are commonly redistributed after each rounds of remeshing. To have a unified field comparison reference mesh model, a mesh grid mapping

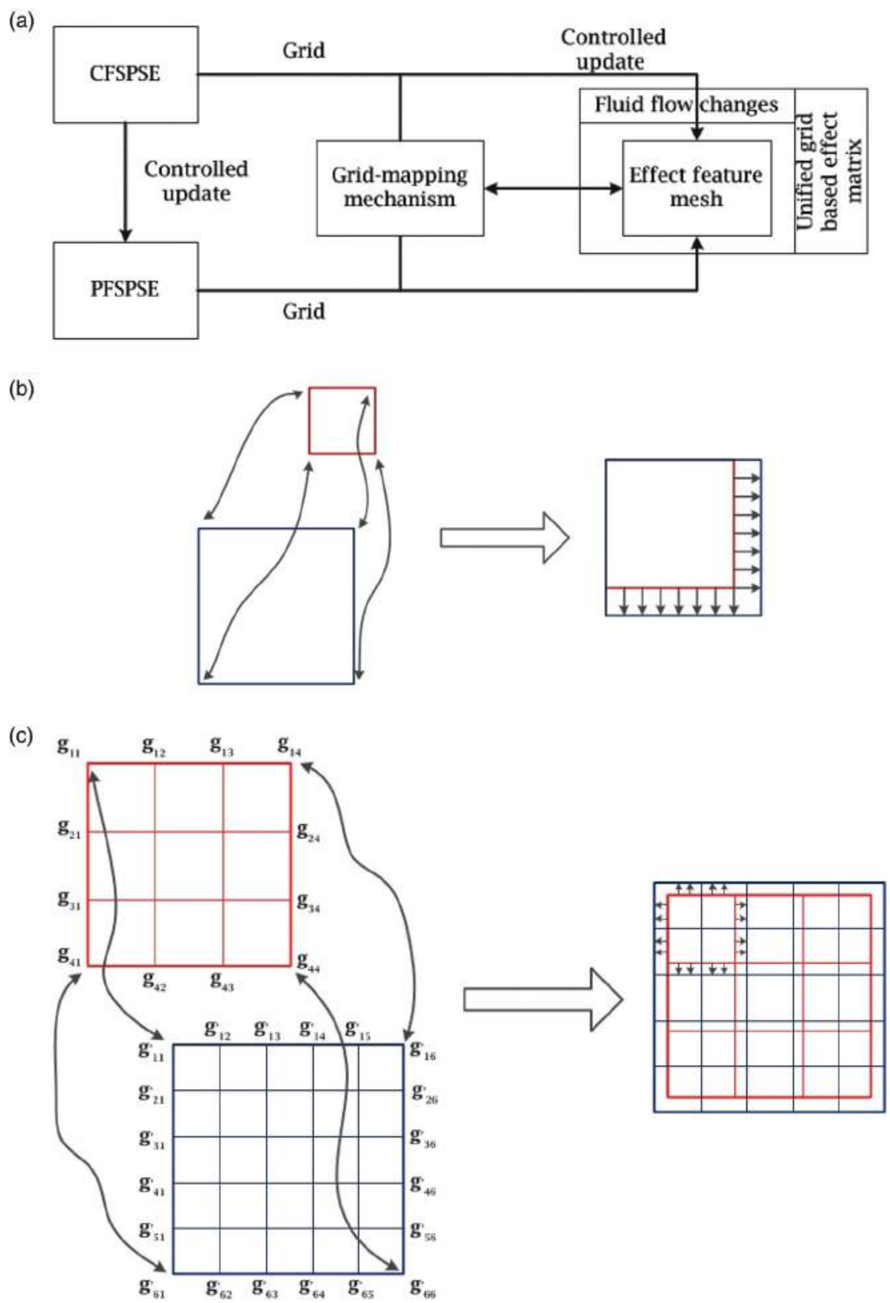


Figure 4. Grid-mapping: (a) Grid-mapping and Property Propagation (b) Grid Scaling, and (c) Grid Scaling and Interpolation.

method is proposed in this work which is illustrated in Fig. 4. The mesh grids generated in CFSPSE according to the mesh distribution and research interest. PFSPSE can be updated by CFSPSE in a controlled manner. The flow properties associated with the grids in CFSPSE and PFSPSE can be compared and unified through the so-called grid-mapping mechanism.

As shown in Fig. 4(a), when the changes of design are minor and the fluid space change does not cause topological change of the fluid space mesh, then by pattern comparison approach, flow states can be measured quantitatively. To support such point-to-point comparison, the grids in the PFSPSE and the CFSPSE must be reasonably corresponding to each other; that means they need to be consistently mapped. This research proposes two types of grid mapping techniques, *scaling* and *interpolation*. As shown in Fig. 4(b), a mesh unit edges in the CFSPSE can be mapped by the scaling factors in both horizontal and vertical directions to compare with PFSPSE; and vice versa. Further, in the case of mesh refinement occurred automatically triggered by the mesher or introduced by the user, as shown in Fig. 4(c), interpolation of grids with the same topological pattern can be worked out to achieve the common and yet the refined mesh grid matrix. Comparing the flow field of CFSPSE with the persistent flow field reference model which is the flow field of PFSPSE, fluid flow changes can be quantitatively revealed by mesh grid-based effect matrix creation. If the user allows, both the mesh of PFSPSE and the persistent flow field reference model can be updated according to new analysis result, thus providing reasonable reference in the next iteration. Overall, the CAE effect features support the CAE to CAD change processes and further help to establish the CAD/CAE integration loop in which consistency maintenance [3] has to be used to update the feature model in different view. The process iterates until an optimal design is obtained.

The prospective system framework is shown in Fig. 5. This proposed system mainly consists of three modules, namely CAD module, CAE module and post-processing module. CAD and CAE modules can be from different commercial software tools which should be capable of complex geometry and analysis. Most commercial CAD systems employ design by feature (DBF) method to build model [7]. DBF is a paradigm in which the geometry is established using features. Typically, there is a feature library in the CAD module to support model creation with DBF. CAD module and CAE module are integrated by associative features [17].

Under the associative feature concept [17], CAD model is mapped to analysis model which can be processed by CAE module. Corresponding CAE features will be extracted to prepare the model for the following calculation in the solver. In the post-processing module, CAE effect feature are extracted with different CAE results from CAE module. Physical reasoning gained from CAE effect feature is sufficient for the optimization of design parameters which will be updated in CAD module. Users can get access to all the modules and functions through user interface.

We acknowledge that not all the features identified by the commercial software represent an interest of analysis. As aforementioned, CAE features are predefined with clear semantic and ontological structures and geometric constituents. With such generic CAE features, a bi-directional reasoning mechanism is proposed. Under this scheme, the forward reasoning proposes potential feature modification options based on empirical formula. Correspondingly, the backward reasoning responds the modification with the changing effect derived. In this

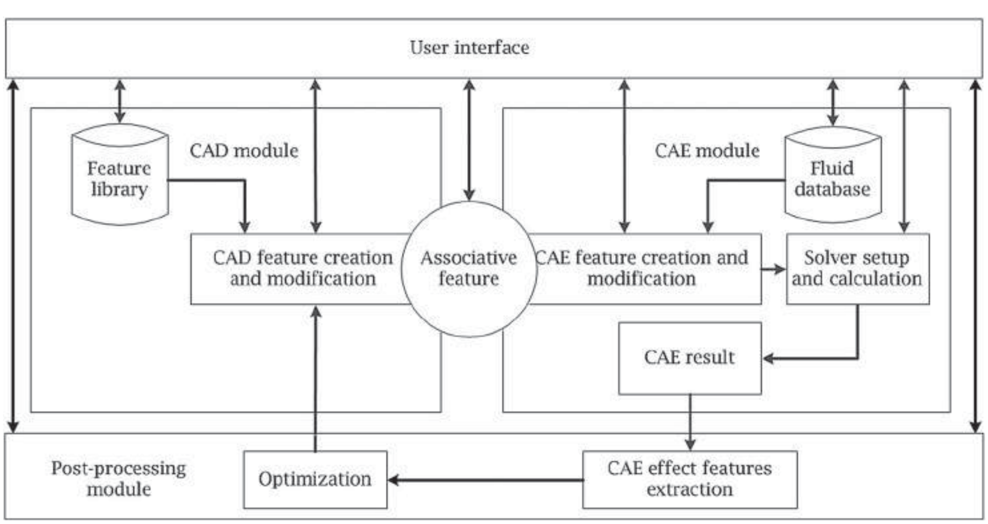


Figure 5. Prospective CAD/CAE Integration System Framework.

way, the sensitivity towards the proposed design change is obtained. This mechanism could be the criteria to identify the feature to be modified.

4. Case Study

The valve design case is studied in this section to prove the effectiveness of our proposed method. The conceptual design is shown in Fig. 6(a), for which the valve sleeve and the valve core are coaxially assembled into the valve body cavity. Functionally, the valve core reciprocates to control the flow loop and rate, and the valve sleeve is applied for replacement purpose because of the excessive wear. The CAD system applied here is Pro/ENGINEER wildfire.

Practically, the erosion caused by excessive hydraulic oil velocity will be significant. As a result, after the design process, analysis on the flow field inside the valve should be conducted to check whether the maximum velocity exceeds the allowance. Here, the P-A valve chamber is studied, which has a high flow rate as it controls the movement of the actuator. In order to process the FEA, the fluid space should be extracted. By using Boolean operation, the fluid space could be obtained with tags assigned, which is shown in Fig. 6(b). It is worth noting that tags with attribute of wall will be assigned automatically after the setup of tags I, O and S because the majority of the faces are wall boundaries. Obviously, after the substantiation of the fluid space, it shares the same face formed by the inner face of valve body, the face of the valve sleeve and the outer face of the valve core. Hence, geometrically, CAD features and CAE features are associated intimately.

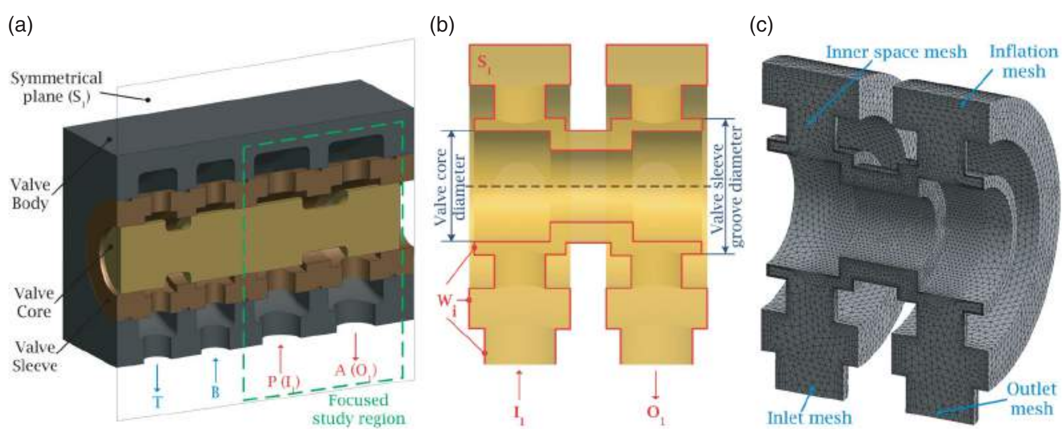
In this case, the fluid dynamic analysis software Fluent is applied. The mesh shown in Fig. 6(c) is generated by ANSYS Meshing module. Inflation mesh distributes along the wall boundary to increase the simulation accuracy in the corresponding areas. The overall information of this model is listed as follows.

- Valve core diameter: 110 mm;
- Medium:
  Type: Hydraulic oil
  Density: 870 kg/m^3
  Dynamic viscosity: 0.04 kg/m·s;
- Analysis type: Velocity analysis;
- Boundary conditions:
  Inlet P: Hydraulic oil velocity 16 m/s
  Outlet A: Hydraulic oil pressure 20 MPa;
- Objective: Maximum hydraulic oil velocity < 27 m/s.

Fig. 7(a) shows the result of the FEA. It is obvious that the maximum velocity is approximately 34 m/s, which exceeds the limitation. This result indicates that with the specified design parameters, the valve could not provide the desired flow rate with a proper maximum hydraulic oil velocity inside the valve. Hence, further modification is needed to meet the requirement.

According to empirical formula, the valve core diameter is determined by flow rate. This provides the forward physical reasoning for optimization. The modification of valve core diameter may be an effective method to optimize the design. In order to support the consistent design throughout the concurrent engineering life cycle, fluid space faces should be associated with the faces of valve body, valve sleeve and valve core. If the design parameters are modified, the fluid space can be updated accordingly. With the single change in the diameter of the valve core, the corresponding modifications on CAD and CAE features are supposed to be conducted automatically. Consequently, the inconvenience induced by the modification on the model will be eliminated.

Extracting the CAE effect feature is an important procedure to get an optimal design. The valve core diameter



T: Return outlet; B: Inlet B; P (I_1): Pressure Inlet tagged #1; A (O_1): Outlet A tagged #1;
S_1: Symmetry plane tagged #1; W_i: The ith indexed wall

Figure 6. Forward Integration Process: (a) Valve Structure, (b) Fluid Space Abstraction (Sectional View), and (c) Mesh Generation.

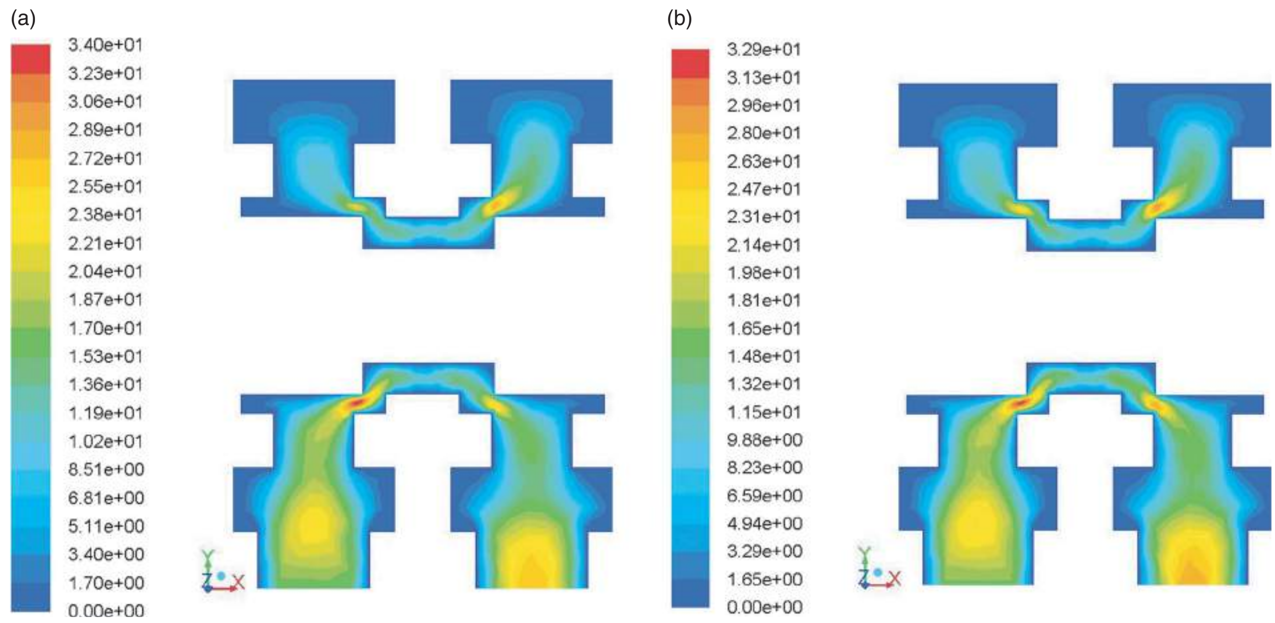


Figure 7. Velocity Distribution: (a) Original Design, and (b) Modified Design.

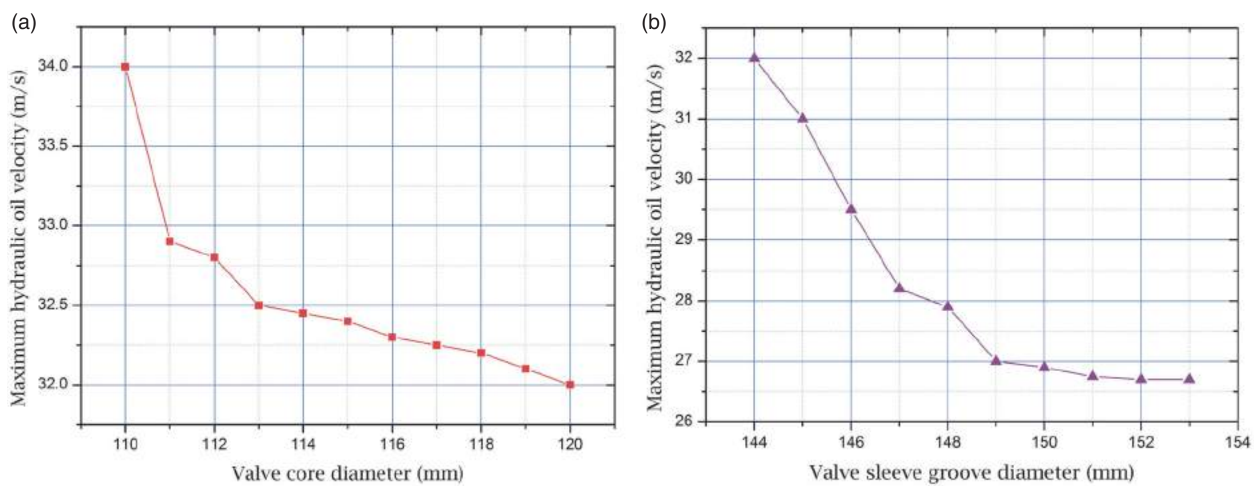


Figure 8. Maximum Velocity: (a) with Different Valve Core Diameter, and (b) with Different Valve Sleeve Groove Diameter.

is increased by 1 mm per step. The velocity distribution after the first valve core modification is shown in Fig. 7(b). The maximum velocity appears to be 32.9 m/s, which decreases in comparison with the original design. It can be concluded that the change of valve core diameter associates with many other design features and CAE features, thus definitely affects the valve performance. It is a reasonable direction to increase the diameter further to see the developing trend. After 9 iterations, the maximum velocities with different valve core diameters are obtained. The maximum hydraulic oil velocity of this iterative process is shown in Fig. 8(a).

Based on engineering knowledge, the increase of valve core diameter is at a cost of material and dynamic performance. In addition, the decreasing rate of maximum velocity is not that fast with the increase of valve core diameter. As a result, the increase of valve core diameter is not an efficient way to optimize the maximum velocity. It can be noticed that in the radial direction, the valve sleeve groove diameter, which is related to the scale of fluid space, is not a matching dimension. As our objective is sensitive to the radial dimension, it is predicted to be another approach to reduce the maximum velocity by increasing the valve sleeve groove diameter directly. Fig. 8(b) shows the analysis results with different valve sleeve groove diameters. All these analyses are carried out based on a fixed valve core diameter, i.e. 120 mm. The modification starts with the initial valve sleeve groove diameter of 144 mm. After this, the valve sleeve groove diameter is increased by 1 mm per step.

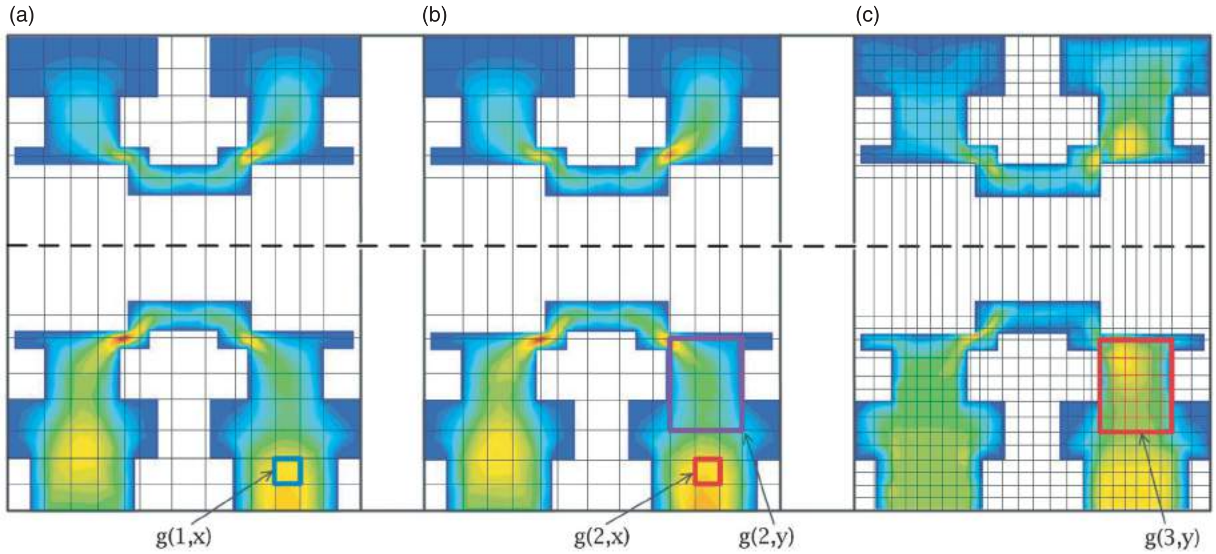


Figure 9. CAE Effect Feature Extraction.

Finally, the maximum velocity falls below 27 m/s leading to the convergence. By extracting the CAE effect feature, the sensitivity towards different parameter change is obtained providing physical reasoning back to CAD modification. Thus, a bi-directional reasoning mechanism is established.

In addition to optimize the physical property of single point of interest, CAE effect feature also demonstrates the effect on the whole fluid domain by grid mapping method. A set of characteristic points are assigned to the locations where interested, which is shown in Fig. 9. Assume Fig. 9(a) shows the PFSPSE. Fig. 9(b) is generated in the process of valve core diameter change while other geometrical features remain unchanged such as the axial dimensions and outer radial boundary. Then the grid mapping between the flow states before and after the change can be done by scaling in each mesh cell in an outward direction. Then the current flow field coupled with grids of CFSPSE is compared with persistent flow field reference model demarcated by PFSPSE. The corresponding scaling can be shown as between cell *g(1,x)* of Fig. 9(a) and cell *g(2,x)* of Fig. 9(b). The error of this proposed mapping is negligible if the step of modification is very small. If the change causes remeshing of the fluid space as shown in Fig. 9(c), then the effect feature extraction needs regional interpolation between PFSPSE and CFSPSE mesh grids as well as the flow property propagation. The corresponding interpolation unification can be worked out as between region *g(2, y)* of Fig. 9(b) and region *g(3, y)* of Fig. 9(c).

The difference in the velocity of corresponding points is calculated after the first modification. Divided by the change in valve core diameter, the velocity change rate can be derived further, which is shown in the following matrix. This is the mathematical form of CAE effect feature, which shows the area and intensity of influence. In this matrix, along with the increase of valve core diameter, positive values indicate the velocity increases and the negative ones for the velocity decreases. Moreover, each point's sensitivity towards the change of valve core diameter is reflected by the value, which is of great significance to the further optimization. For instance, local large velocity is one of the causes of hydraulic shock. The extraction of CAE effect feature can identify the region related to hydraulic shock and provide efficient method to mitigate even eliminate this phenomenon.

$$\frac{\partial V_x}{\partial D_c} = \begin{bmatrix}
-0.08 & -0.08 & -0.08 & -0.08 & & & & & -0.08 & -0.20 & -0.20 & -0.08 \\
 & -0.25 & -0.25 & & & & & & & 1.33 & 1.33 & \\
 & -0.25 & -0.40 & & & & & & & -0.45 & -0.40 & \\
-0.03 & -0.08 & -0.36 & -0.70 & & & & & -0.95 & -0.40 & -0.08 & -0.03 \\
 & & & & -0.40 & -0.40 & -0.40 & -2.06 & & & & \\
 & & & & -0.55 & -0.45 & -0.40 & -2.10 & & & & \\
-0.08 & -0.19 & -0.45 & -1.05 & & & & & 2.45 & 1.3 & -0.14 & -0.08 \\
 & -0.50 & -0.50 & & & & & & & -0.40 & -0.40 & \\
 & -0.50 & -0.50 & & & & & & & -0.40 & -0.40 & \\
-0.20 & -0.60 & -0.60 & -0.20 & & & & & -0.20 & -0.40 & -0.40 & -0.20 \\
 & 1.00 & 1.00 & & & & & & & 1.05 & 1.05 & \\
 & -0.65 & -0.65 & & & & & & & -0.70 & -0.70 &
\end{bmatrix}$$

As is shown in the matrix, the majority of the points' velocity decreases with the increased valve core diameter, and the changes are more remarkable in the areas where the flow channel changes greatly. In each of the iterations, the matrix is checked for the validity of the modification method.

5. Conclusions

This paper explores a mechanism of CAD/CAE integration based on the concept of *associative feature*. An overall feature mapping framework for persistent associations for CAD/CAE interactions has been suggested. This framework can effectively represent cyclic knowledge of product design, CAE evaluation, change justification and optimization, and design evolvement. Through a case study, it is clear that the associations between CAD model and CAE analysis can be achieved. It can be concluded that associative feature is an effective mechanism of managing not only geometric associations, but also semantic portions of the features.

The concept of CAE *effect feature* is proposed for the first time, enabling the realization of the integrated loop of CAD/CAE sessions with effect comparison over the changes. In addition, the interpretation of CAE effect with features provides a consistent way to measure the optimization results and navigate its procedure which so far cannot be solved by CAE methods. This work is currently focused on the CAD/CAE interaction mechanism related to fluid dynamics; the example illustrates the design process of a hydraulic valve. As an objective, the maximum velocity in the valve flow field is studied and the CAE effect features are extracted which leads to an optimized design.

The consistency and accuracy of integration is maintained by introducing another new CAE feature, CAE *boundary feature*. CAE boundary features model and represent boundary conditions during iterations and achieve associated mesh regeneration for solver setup. At this stage, the authors are encouraged by the generic capability of the integration method and are not aware of any limitation of the proposed approach so long the optimization space keeps the similar topology. Further research needs to be conducted to reveal the efficiency and deficiency.

As to future work, under this proposed associative CAD/CAE integration scheme, prototyping of automated functions is to be carried out to provide implementation proof. Further, it is worthwhile to study the accurate extraction of CAE effect features with less computational cost. A CAE analysis interpretation method is expected to conduct optimization of the physical field, and thus controlling the corresponding phenomena.

Acknowledgement

The authors would like to acknowledge the financial support from China Scholarship Council, University of Alberta Doctoral Recruitment Scholarship, NSERC Discovery Grant and RGL Collaboration Fund.

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