Knowledge-Based Robust Piping Design

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Abstract

Substantial reduction of the cycle time between the piping layout design and the stress analysis is still a challenge that engineering, procurement and construction (EPC) are facing. This paper discusses such a design problem. The research proposes a knowledge-based expert system, which integrates professional knowledge and codes, expert experiences, and the effective robust design concept, in order for piping designers to create ready-to-approve layouts in an easy and fast way. This paper aims to eliminate the unnecessary cycle time for the current design procedure – not to change the procedure.

Keywords: Robust Design, Piping Design

Introduction

In piping design, efforts have been made to reduce the cycle time between the proposed piping layout and the stress analysis. Canadian EPC companies generally have two groups – the design group and the stress group that work on piping layout. The problem arises due to the current workflow – normally the piping designer generates the layout design, then the piping engineer conducts the stress analysis. If there are stress problems, the feedback will be given to the designer who re-lays out the pipes and submits to the engineer again. This iterative process keeps going until the design

is approved. The designer usually has little knowledge of stress analysis and structural optimization. They design the layout according to the specification, the experience and the engineer's draft design requirements. Meanwhile, the engineer is seldom responsible for designing piping layout. He/she finds problems and asks designers to redesign.

For such a problem, many design handbooks [1] would recommend a set of table and diagrams to assist the designer to design the supports with suggested spans. A research on a pipe support design aims to optimize the design among those pre-designed supports, eliminating some supports based on the analysis [2]. A software tool available in the market is called PSO. It identifies pipe support locations according to practical distances from supportable structures. Only feasible support locations (most are edited manually) are considered for pipe support location optimization. The optimization actually is the stress analysis process, which is now done by the piping engineer.

Above practices have one thing in common which is designing all potential supports with the layout first based on the previous design experience and then optimizing them. In reality, they are not real optimizations. It's a technique to test and see which of those pre-designed supports are "better" than the others. From the viewpoint of robust design, the problem can be summarized as below:

1. Piping system's reliability highly depends upon the stresses and displacements;

2. The stresses and displacements may be caused by the system's static loadings, dynamic loadings, and thermal effects;
3. If the system can be designed such that its stresses and displacements are least sensitive to the changes of those loadings and thermal effects, then its design is robust.
4. Theoretically, Robust Design can have two levels of application in regard to the piping design – static application only and all purpose application (covering static and dynamic). The second level application may get involve every aspect of piping design and analysis process which may lead to a systematic approach to piping systems. However, that is not our purpose in this discussion. Our goal is to eliminate the unnecessary iteration time for the current design procedure – not to change the procedure.
5. Thus, the goal can be achieved by applying robust analysis techniques during the piping design stage. According to the present industrial practices, we only need to consider static loadings and thermal effects during this stage.
6. In respect to the traditional design method, most feedback from the engineer would suggest designers to change supports' positions or occasionally change the layout. That is because designers arrange those supports mainly based on their previous industrial experience.

Regarding the work process, it may vary depending on different plants. According to [1], a typical work flow (as indicated in figure 1) may start from the identification of the critical line list. The designer prepares the preliminary isometrics. The engineer applies stress analysis onto those isometrics. The analyses may suggest the designer to make revisions until the stress results get improved and acceptable. Then, it goes to the conceptual studies. The designer can expect to receive more feedbacks related to those non-critical lines. Beyond this point, the designer works on 3D modelling based on the approved

Figure 1. Pipe Stress Work Process [1]

conceptual design. Finally the isometrics are extracted from the 3D models and approved by the engineer.

Designers' major task is to generate the draft layout designs. They use the design application tools, such as AutoCAD, AutoPlant, SolidWorks, etc., to create a 2D/3D layout and send to an engineer for approval. On the other hand, engineers may use the analysis tool, such as AutoPipe, CAEPIPE, etc., to check and analyze the structural stress. Based on the analytical result and their experience, they would keep finding problems and kicking the layout design back to the designer for redesign until it got approved. The longer cycle time exists for the following reasons:

- Designers can only use the design software. They don't have enough knowledge to use the analytical FEA tools and to understand the respective results.
- Engineers can use and understand the analysis software. However, they are not expected to spend time on CAD drawing and redesigning, but instead they provide critical suggestions as

experts.

To reduce the cycle time means the layout design must be good enough and need few changes when it gets to the engineer so that it can be approved quickly. This can be possible only if

- The designer knows better of structural stress and completes both design and analysis; or the engineer can do both design and analysis by him/her own – one person does all.
- The layout design is robust from the very beginning so that it is ready to approve when it comes onto the engineer's table.

Obviously, it is not cost-effective if both engineers and designers are required on the same education level. However, it is still possible for one person to do all required things. Notice that the stress problems can always be solved by adjusting the layout. And all activities to do this are regulated by the professional codes, technical knowledge and former experience – all are rule-based stuffs. Thus, the solution is an AI tool – a knowledge-based expert system that can help designers to complete the tasks formerly done by engineers. As a tool, it is also possible to integrate the robust design technique to maximum reduce the iteration times. How to apply Robust Design? The following section focuses on this topic.

Robust Design and Discussion

Some of the mechanical system designs are found to be better or more robust than the others. One of the research efforts is to find a way to achieve “good” or optimal designs. Suh [3] proposed an Axiomatic Design theory, which consists of two axioms: independence axiom and information axiom. This theory defines ideal designs that obey the independence axiom. However in reality, not all designs can be functionally independent but still serve the purpose.

On the other hand, it is always desirable that the product performances are not affected or minimally

affected by their operation environment, which is called robustness. Designers pursue the robust design all the time. The robust design is such a design that satisfies design requirements while minimizing the effects of the environmental variability on the product performance [4]. Those environmental variations may include raw materials, manufacturing processes, and/or operational environments that can cause deviations of the product performances and functions. This thesis will verify that the independence axiom can always lead to a robust design, while the robust designs do not necessarily require the independence. Thus, the designs may be divided into three categories: feasible designs, robust designs, and ideal designs. It is understandable that sometimes it is not always possible for the designers to achieve the ideal goals. A possible approach is first to generate a feasible design, then seeks to acquire the robustness, and then achieve the possibility of the independence.

Currently, it is difficult for the engineers to analyze their designs' robustness and independence in a single framework. The functional evaluation scientifically analyzes the physical structure to achieve best design results. While Taguchi method provides a system that can lead to a robust design, Axiomatic Design assists engineers to achieve an ideal design. Because Axiomatic Design targets on the ideal design, it does not support any other designs that do not obey the independence axiom. Axiomatic Design is a foregoing design theory. Taguchi method is an experimental system-based traditional robust engineering technique that is not directly related to the independence concept [5]. These are different techniques and concepts that are difficult to integrate together. A unified framework would benefit the design and analysis processes and may help to reach the best design goal – to be ideal or at least robust. This thesis will come up with such a framework that deals with both independence and robustness of the design. It introduces the integration of the independent analysis, which is based on Suh's Axiomatic Design, and robust analysis, which is based

on the traditional robust technique. It can help the designer to seek an ideal design or a robust design in respect to the specific design conditions. Some designs may not be ideal or robust. Then the designers need to decide to keep the designs or to make some changes to achieve the ideal or robust design.

A robust design means the designed performance is hardly affected by the environmental variations. The product's ability to fulfill the function is then insensitive, or robust, to the changes from those uncontrollable noise parameters of the environment. Products face environmental variability in respect to raw materials, manufacturing processes, and operational environment, which can cause deviations of the design performance and functions. As discussed above, Axiomatic Design can lead to an ideal design only if the independence axiom is verified, which means it must be an uncoupled design. In some cases, the decoupled designs are also acceptable because they may become independent under the specific conditions. However, the decoupled design may not be robust for the potential environmental variations.

According to Suh's theory, the design process can be considered as a procedure mapping from the functional domain to the physical domain [3]. If **Fr** denotes the functional requirement, and **Dp**, the design parameter, then the performance function can be expressed as

$$\mathbf{Fr} = \mathbf{D} \cdot \mathbf{Dp} \quad (1)$$

Where

$$\mathbf{Fr} = [\text{Fr}_1, \text{Fr}_2, \text{Fr}_3, \dots, \text{Fr}_n]^T$$

$$\mathbf{Dp} = [\text{Dp}_1, \text{Dp}_2, \text{Dp}_3, \dots, \text{Dp}_m]^T$$

D is called design matrix. $D_{ij} = \partial \text{Fr}_i / \partial \text{Dp}_j$

When $n > m$, it is a coupled design and $n < m$, a redundant design. Only when $n = m$, it has chance to be an ideal design [3]. Although $n = m$, it still has chances to be a coupled design (which does not obey the independence axiom) or a decoupled design (which may conditionally become independent). In this case, $D_{ij} = 0$ (when $i \neq j$) means uncoupled design; $D_{ij} = 0$ (only when $i < j$) means decoupled design; otherwise D_{ij} means

coupled design. Uncoupled design is the most preferred.

In reality, design parameters in the physical domain may have variations (σ_{Dp}) caused by changes of the environment, including manufacturing, usage, and other environmental factors. Although these variations are unable to be controlled by designers, the performance function may not be sensitive to those changes. This is still robust.

Mathematically, the covariance and variance-covariance are often used to measure a certain kind of dependence between the variables.

Thus,

$$\mathbf{Fr} = \mathbf{D} \cdot \mathbf{Dp}$$

$$\text{VC}(\mathbf{Fr}) = \text{VC}(\mathbf{D} \cdot \mathbf{Dp}) \quad (2)$$

$$\text{VC}(\mathbf{Fr}) = \text{E}[(\mathbf{D} \cdot \mathbf{Dp}) \cdot (\mathbf{D} \cdot \mathbf{Dp})^T] \quad (3)$$

$$\text{VC}(\mathbf{Fr}) = \mathbf{D} \cdot \text{VC}(\mathbf{Dp}) \cdot \mathbf{D}^T \quad (4)$$

When **Fr**s are independent to each other. The variance-covariance is just the variance itself. **Dps** have the same story.

$$\mathbf{S}_v = \mathbf{D} \cdot \mathbf{D}^T \quad (5-1)$$

Where

$$S_{vi} = (\sigma_{\text{Fri}} / \sigma_{\text{Dpi}})^2 \quad (5-2)$$

Assuming there is a uniform S_v when the design equations and parameters represent the same types of physical relations and properties.

$$S_{vi} = (\sigma_{\text{Fri}} / \sigma_{\text{Di}})^2 = S_v \quad (6)$$

Then,

$$\mathbf{S}_v = S_v [\mathbf{I}] = \mathbf{D} \cdot \mathbf{D}^T \quad (7)$$

It is called the sensitive matrix here.

$\mathbf{D} \cdot \mathbf{D}^T = S_v [\mathbf{I}]$ means **D** and $\mathbf{D}^T$ can be inversed each other and **D** is an orthogonal matrix:

$$\mathbf{D}^{-1} = \mathbf{D}^T \quad (8)$$

Thus,

$$\mathbf{D}^{-1} \cdot (\mathbf{D}^T)^{-1} = \mathbf{D}^T \cdot \mathbf{D} \quad (10)$$

The orthogonal transformation,

$$\mathbf{D}^T \cdot (\mathbf{D} \cdot \mathbf{D}^T) \cdot \mathbf{D} = \mathbf{D}^T \cdot (S_v [\mathbf{I}]) \cdot \mathbf{D} = S_v \mathbf{D}^T \cdot \mathbf{D} \quad (11)$$

Thus, we have,

$$\text{tr}(\mathbf{D}^T \cdot \mathbf{D}) = \text{tr}(\mathbf{D} \cdot \mathbf{D}^T) = \text{tr}(S_v [\mathbf{I}]) = n S_v \quad (12)$$

Then we have norms,

$$\| \mathbf{D} \|_F = [\text{tr} (\mathbf{D} \cdot \mathbf{D}^T) / n]^{1/2} = S_v^{1/2} \quad (13)$$

$$\begin{aligned} \| \mathbf{D}^{-1} \|_F &= [\text{tr} [\mathbf{D}^{-1} \cdot (\mathbf{D}^{-1})^T] / n]^{1/2} \\ &= [\text{tr} [\mathbf{D}^T \cdot (\mathbf{D}^{-1})^{-1}] / n]^{1/2} \\ &= [\text{tr} (\mathbf{D}^T \cdot \mathbf{D}) / n]^{1/2} \\ &= S_v^{1/2} \end{aligned} \quad (14)$$

With these norms, the condition number can be derived.

$$K_f = \| \mathbf{D} \|_F \| \mathbf{D}^{-1} \|_F = S_v^{1/2} S_v^{1/2} = S_v \quad (15)$$

According to the property of Condition Number, if K is relatively small, the matrix is called a well-conditioned matrix; otherwise, it is ill-conditioned. Thus, when the design brings out vector $\mathbf{Fr}$ (functional requirements) and $\mathbf{Dp}$ (design parameters ~ physical parameters), as well as their performance matrix $\mathbf{D}$, it can be determined whether the design is independent and robust.

The derived sensitive matrix S_v or the condition number K can definitely be used onto the product design. A design that satisfies the following conditions is considered robust:

1. S_v is a diagonal matrix, and
2. Values of the elements on the diagonal should be identical and relatively small.

Knowledge-Based System

The developed Robust Design framework provides a right way to solve the problem from a theoretical perspective. The other major reason for the cycle time problem, as mentioned above, dues to the difference of knowledge levels of the design group and the stress group. This makes it possible to apply knowledge engineering and artificial intelligent techniques in this area. A design system can be developed to do most things of the layout design and the stress analysis. It is a knowledge-based expert system, in which relative rules in terms of robust design criteria, professional knowledge, industrial codes and expert experiences are collected. It functions as a “person” who is able to look after most tasks formerly done by designers and engineers. The idea is

Figure 2. Piping Expert System

to develop a tool that can be used by designers and help to accomplish everything after the first draft layout is created. The system can take in the draft layout design with the standard format. Based on the robust design rules, the system analyzes it and redesigns the layout towards robustness. Then, it is send to a pre-selected CAE environment for analysis. The system gets the feedback from that CAE tool and makes changes to the design model based on the rules collected in the knowledge base of the system. The revised design, then, is sent to the CAE-environment again and gets reassessed. This process will continue until the system considers the changed design fulfills the requirement.

The system has four interfaces, the user interface to setup the conditions and select the format which can be matched by the pre-selected CAD and CAE tools, the CAD interface to communicate with CAD applications, the CAE interface to exchange data with CAE applications, and the expert interface to update the knowledge base in the system.

Currently the research group and EPC partners are working together, collecting necessary knowledge for the system.

The following example is to demonstrate the developed robust design framework works on piping.

Piping Supports

The piping structure is considered as a statically

indeterminate system. It can be separated into elements. Each element's stresses can be calculated in terms of its static loadings and temperature changes. In this research, "Z" section was selected as it most likely had the negative reaction force with worse stress, if the support's location was not selected correctly. As shown in Figure 3, an 8" pipe comes from Point A and goes along X direction. From Point B, it goes to C along Z direction, and then continues to go along X direction to D. At the beginning, the designer may create this based on the experienced span requirement.

Figure 3. Original Design

Following the current design method, the designer would normally arrange a group of supports with a span of 15 feet for each pair in regard to A53 steel shown in Figure 3. Is this arrangement a robust design? Mechanically, the design can be simply modeled as "Z" structure with three supports as indicated in Figure 4. In another words, the pipe section between support 3 and 5 is considered. Its static loading includes the uniform weight and two moments at each end due to the internal actions of the separation from the other parts. Based on structural mechanics, this is a statically indetermined structure that can be divided into two pipe elements. For the piping system, the stress is the major concern during the design and analysis. Any cross section's stress can be calculated using its internal moment. Obviously, for this structure, the maximum moments will occur at those position of the supports. Thus, the robustness may be achieved when the stresses are insensitive to loading changes. In turn,

this requires that the moments be insensitive to those variations of supporting forces, which are determined by the loading.

Support B's location will be decided by the following calculation. Element 3-B-4 consists of 3-B and B-4 pipes. The lengths and weights are denoted by L_{3B} , L_{4B} , W_{3B} , and W_{4B} respectively. Element 4-C-5 consists of 4-C and C-5 pipes. Their lengths and weights are denoted by L_{4C} , L_{5C} , W_{4C} , and W_{5C} .

Because

$$\sum M_x = 0, \sum M_z = 0, \sum F_z = 0$$

Thus,

$$M_{3z} = R_{3y} \cdot L_{3B} - W_{3B} \cdot L_{3B} / 2$$

$$M_{4x} = R_{4y} \cdot L_{4B} - W_{4B} \cdot L_{4B} / 2, \text{ or}$$

$$M_{4x} = R_{4y} \cdot L_{4C} - W_{4C} \cdot L_{4C} / 2$$

$$M_{5z} = R_{5y} \cdot L_{5C} - W_{5C} \cdot L_{5C} / 2$$

$$R_{3y} + R_{4y} + R_{5y} = W_{3B} + W_{4B} + W_{4C} + W_{5C}$$

Figure 4. Structural Analysis

The above functions represent the mechanical relationship between the structural strength, supports, and loads.

If performance function $\mathbf{Fr} = \mathbf{D} \cdot \mathbf{Dp}$ is constructed as

$$\mathbf{M} = \mathbf{D} \cdot \mathbf{R}$$

Where

$$\mathbf{M} = [M_{3z}, M_{4x}, M_{5z}] \text{ and } \mathbf{R} = [R_{3y}, R_{4y}, R_{5y}]$$

Then,

$$\mathbf{D} = \begin{bmatrix} \partial M_{3z} / \partial R_{3y} & \partial M_{3z} / \partial R_{4y} & \partial M_{3z} / \partial R_{5y} \\ \partial M_{4x} / \partial R_{3y} & \partial M_{4x} / \partial R_{4y} & \partial M_{4x} / \partial R_{5y} \\ \partial M_{5z} / \partial R_{3y} & \partial M_{5z} / \partial R_{4y} & \partial M_{5z} / \partial R_{5y} \end{bmatrix}$$

According to the above equations, the following relationships can be derived.

$$\partial M_{3z} / \partial R_{3y} = L_{3B},$$

$$\partial M_{3z} / \partial R_{4y} = 0,$$

$$\partial M_{3z} / \partial R_{5y} = 0$$

$$\partial M_{4x} / \partial R_{3y} = 0,$$

$$\partial M_{4x} / \partial R_{4y} = L_{4B},$$

$$\partial M_{4x} / \partial R_{5y} = 0$$

$$\partial M_{5z} / \partial R_{3y} = 0,$$

$$\partial M_{5z} / \partial R_{4y} = 0,$$

$$\partial M_{5z} / \partial R_{5y} = L_{5C}$$

Thus, the design matrix is

$$\mathbf{D} = \begin{bmatrix} L_{3B} & 0 & 0 \\ 0 & L_{4B} & 0 \\ 0 & 0 & L_{5C} \end{bmatrix}$$

The sensitive matrix will be

$$\mathbf{D} \cdot \mathbf{D}^T = \begin{bmatrix} L_{3B}^2 & 0 & 0 \\ 0 & L_{4B}^2 & 0 \\ 0 & 0 & L_{5C}^2 \end{bmatrix}$$

According to the sensitive matrix's characters,

$$L_{3B}^2 = L_{4B}^2 = L_{5C}^2$$

If using

$$M_{4x} = R_{4y} \cdot L_{4C} - W_{4C} \cdot L_{4C} / 2,$$

then the following expression can also be derived,

$$L_{3B}^2 = L_{4C}^2 = L_{5C}^2$$

The relationship is expressed as

$$L_{3B}^2 = L_{4B}^2 = L_{4C}^2 = L_{5C}^2$$

Thus,

$$L_{3B} = L_{4B} = L_{4C} = L_{5C}$$

This is the condition for the design to achieve its robustness. The result indicates that 3-B, B-4, 4-C, and C-5 have the same length. As shown in Figure 5, when the physical structure is designed with $L_{3B} = L_{4B} = L_{4C} = L_{5C}$, it is robust.

Figure 5. Robust Design

The above work can be done through the computer calculation, including checking robustness, exchanging data with CAD and CAE applications, revising the layout, displaying design and analysis results, and outputting design documents.

Summary

Robust Design methodology, together with professional piping knowledge, industrial codes, and expert experiences, can be applied to build up a knowledge-based expert system. As a general approach, the robust design and analysis can achieve the design goals by analyzing the design matrix of the performance function which indicates if obeys the independence axiom and/or robust requirement. Thus, it is possible for such a system to automatically accomplish most works which are usually done by both the designer and the engineer. Then, the cycle time between layout design and stress analysis can be significantly reduced.

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