The application of CAD, CAE & CAM in development of butterfly valve’s disc

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Abstract. The improved design of a butterfly valve disc is based on the concept of sandwich theory. Butterfly valves are mostly used in various industries such as oil and gas plant. The primary failure modes for valves are indented disc, keyways and shaft failure and the cavitation damage. Emphasis on the application of CAD, a new model of the butterfly valve’s disc structure was designed. The structure analysis was analysed using the finite element analysis. Butterfly valve performance factors can be obtained is by using Computational Fluid Dynamics (CFD) software to simulate the physics of fluid flow in a piping system around a butterfly valve. A comparison analysis was done using the finite element to justify the performance of the structure. The second application of CAE is the computational fluid flow analysis. The upstream pressure and the downstream pressure was analysed to calculate the cavitation index and determine the performance throughout each opening position of the valve. The CAM process was done using 3D printer to produce a prototype and analysed the structure in form of prototype. The structure was downscale fabricated based on the model designed initially through the application of CAD. This study is utilized the application of CAD, CAE and CAM for a better improvement of the butterfly valve’s disc components.

1. Introduction
Butterfly valve is widely used in various application especially in industrial sector. A butterfly valve is a simple mechanical operation device preferable for separate or isolate a process and regulate a fluid flow for a certain distance. Industrial sector generally favored butterfly valve due to their lower in cost to other valve designs as well as being lighter in weight, meaning less support is required. Butterfly valve consists of body, disc, stem, and seat. Most of butterfly valve are not applicable for a high pressure fluid flow. The design of the butterfly valve are based on the principle of pipe damper. Element that control the flow which is the disc, acts like a gate and has approximately the same diameter as the inside diameter of the pipe joint [2].

A butterfly valve consists of a circular disc or plate built with a stem through the middle or attached offset. The disc is positioned in the center of the pipe, passing through the disc is a rod connected to an actuator on the outside of the valve. The disc manufactured based on the solid element design. Based on the review that had been done, butterfly valve’s disc experience failure due to certain aspects. The first failure is the shaft-disk separation due to pin failure [7]. An incident occur in the 1997 involve the pin connected to the shaft and disc. Another way failure is when the butterfly valve experience disc tear (Indented disc). This happen because of the presence of foreign object inside a pipeline flow and the number of valve usage [11].The final problem is due to the presence of cavitation on the low region inside the pipeline flow. High pressure differential between the upstream and downstream of
the flow is the main cause of the cavitation [1]. The disc structure of the butterfly valve is based on two consideration of analysis. The first one is the Computational Fluid Dynamics (CFD) and the Structural Analysis using the Finite Element Analysis (FEA). The structure analysis is to analyze the condition of the disc structure and determine the weaker section of the disc and determine the condition of the structure if there is any failure. CFD application is to determine the flow of the fluid in pipeline with the designed model of the disc. This will determine the area of low pressure on the downstream inside the pipeline for cavitation justification.

2. Problem Identification

The most common failures of butterfly valve were described in the following subsections.

2.1.Indented Disc

Foreign particle that travel at high speed inside the pipeline system course the disk from the butterfly valve being indented and as days passed by, the disk will corroded and will experience metal lost. Figure 1 shows the corroded disc. As a result, the butterfly valve experience leakage and ultimately it will not block the flow of the gas. The sandwich-structured of composite is a unique and special class of composite materials. Attaching two thin but stiff skins to a thick core but lightweight, the composite materials was fabricated. The core material is normally low strength material, sandwich composite with high bending stiffness due to its higher thickness and overall low density [1].

2.2. Pin and Keyways Failure

Butterfly valve was design with a drive shaft that connects the internal valve disk to an external pneumatic cylinder (actuator). The valve fail when a dowel pin design to fasten the dry shaft to the key shared and key design to transfer torque from the driver shaft from the disk. System pressure was high enough to eject the unrestrained drive shaft from the valve carry with it external counterweight [1].

A number of design may contribute to this hazard. These include the valve has a shaft or stem piece which penetrates the pressure boundary and ends inside the pressurized portion of the valve. This feature results in an unbalanced axial thrust on the shaft which tends to force it (if unconstrained) out of the valve. Figure 2 shows the current disc design of the valve. The second design problem is that valve contains potential internal failure points, such as shaft dowel-pins, keys, or bolts such that shaft-disk separation can occur inside the valve [6].

The third problem is that the dimensions and manufacturing tolerances of critical internal parts (e.g., keys, keyways, pins, and pin holes) as designed or as fabricated cause these parts to carry abnormally high loads (e.g., in the 1997 accident, the dowel pin rather than the key transmitted torque from the shaft to the disk). The final concern on the design problem is that the valve stem or shaft is not blow-out resistant. Non blow-out resistant design features may include two-piece valve stems that penetrate the pressure boundary (resulting in a differential pressure and unbalanced axial thrust as
described above), single-diameter valve shafts (i.e., a shaft not having an internal diameter larger than the diameter of its packing gland) or shafts without thrust retaining devices. A Hobbs triple offset butterfly valves require no pins and keyways on the shaft that will connected to the disc. Replacing the pins with bolts, the disc directly bolted to the shaft and this eliminates the problems of a weaker shaft and the problem of shearing during high velocity applications. The keyways of the shaft was eliminated by using the square shaft, the keyways will not be required anymore [5].

2.3. Cavitation Damage
When a butterfly valve is used for throttling or modulating flow rates, the operating conditions should be evaluated to determine whether significant cavitation will occur. Cavitation can cause objectionable noise, vibration, and decrease the useful life of a valve and nearby piping components [3]. Figure 3 shows the disc was damaged due to cavitation. Cavitation is the vaporization and subsequent violent condensation of a fluid caused by localized areas of low pressure in a piping system. When water flows through a partially open butterfly valve, a localized low-pressure zone may occur immediately downstream of the valve disc because of the sudden changes in flow velocity and flow separation. When the pressure in this zone falls below the vapor pressure of the fluid, the liquid vaporizes, forming a vapor pocket or vapor bubbles. As the bubbles flow downstream and the pipeline pressure recovers, the bubbles violently collapse or implode.

![Figure 3. Cavitation Damage](image)

Cavitation can form in a butterfly valve immediately downstream of the valve disc where a low-pressure zone occurs. Cavitation bubbles can implode just downstream of the disc or many times the pipe diameter downstream, depending on where the pressure recover. The process produces an unmistakable noise and vibration that sound like gravel flowing through the pipe. Many simple shutoff valve applications produce cavitation when the valves are near the closed position, because the differential pressure reaches its highest level at that point. However, since a shutoff valve is usually at a near-closed angle for only a short period of time, appreciable damage to the valve or piping usually does not occur. When a valve is exposed to caviting condition continuously, however, such as when it is used for flow modulation or pressure control, significant damage can occur to the metal surfaces of the valve or downstream piping in a short period of time [3]. Figure 3 shows the cavitation effect.

2.4. Predicting Cavitation
Three terms are commonly used to classify cavitation in valves according to the Instrument Society of America namely Incipient cavitation, constant cavitation and choked cavitation. The start of steady cavitation, termed incipient cavitation, can be indicated by an intermittent popping sound in the flow stream. Incipient cavitation typically does not cause damage or objectionably loud noise. If the pressure differential increases, however, the constant cavitation level is reached, which can be indicated by a continuous popping similar to the sound of gravel flowing through the pipe or bacon frying. Continuous flow above the constant cavitation level is often accompanied by objectionable noise and valve or piping damage. The choking cavitation level occurs when the valve is passing the maximum flow possible for a given upstream pressure. The vapor pocket may become extremely long,
causing damage far down-stream from the valve. Choking cavitation may cause a reduction in noise, but this change is usually preceded by the highest level of noise and vibration. Tests have shown that conditions likely to produce cavitation in a butterfly valve can be predicted and possibly reduced or prevented. The cavitation index is typically used as a predictor of valve damage and is expressed quantitatively at each valve angle as follows:

$$\sigma = \frac{(P_u - P_v)}{(P_u - P_d)}$$  \hspace{1cm} (1)

### Table 1. Variable and Definition of cavitation index

| Variable | Description                                                                 | Units US Customary (SI-metric) |
|----------|-----------------------------------------------------------------------------|---------------------------------|
| $P_d$    | Reference downstream pressure for cavitation analysis                        | psi (kPa)                       |
| $P_u$    | Reference upstream pressure for cavitation analysis                          | psi (kPa)                       |
| $P_v$    | Vapor pressure adjusted for temperature and atmospheric pressure. (Example: $P_v = -14.4$ psig [-99.6 kPa] for water at 60° F [16° C], (kPa) measured at sea level). | psi (kPa)                       |
| $\sigma$ | Cavitation index, general form                                              | dimensionless                   |

Cavitation indices for, constant, and choked levels can be determined from flow testing in a laboratory environment. The operating cavitation index can be compared to the cavitation indices for valves to predict what level of cavitation will occur (incipient, constant, or choking). It should be noted that in some earlier texts the constant index is referred to as critical. Later texts change this nomenclature to constant to be more descriptive of the condition without implying a crucial operating condition. Cavitation indices for incipient, constant, and choked levels can be determined from flow testing in a laboratory environment. Cavitation can be observed using a hydrophone or accelerometer during the flow test. The lower the calculated cavitation index, the greater the likelihood of cavitation damage. For example, if a valve is throttled at 45" open with a calculated index of 6.0, then cavitation will likely not occur. If, however, the valve is closed further to 30" open with a calculated index of 2.2, then the cavitation in the range between incipient and constant will occur. Sounds of cavitation will be heard, but serious damage will occur only after a prolonged period of time under those conditions [3]. Figure 4 shows the three different region of the cavitation index.

![Figure 4. Cavitation Index Boundaries](image)

Design provisions for water systems completely without cavitation are beyond the scope of this manual, but some general recommendations to reduce cavitation can be considered. To reduce cavitation, the value of the cavitation index, $\sigma$, must be increased above the constant cavitation index for the valve. One way to do this is to increase the downstream pressure, $P_d$, which will increase the value of the cavitation index. Another strategy is to decrease the differential pressure across the valve.
(P_c - P_d). The value of the constant cavitation index, \( u_c \), can also be changed by using the valve at a different opening position or using a different valve model. Finally, air can be introduced to mitigate cavitation.

3. Methodology

3.1 Computer Aided Design (CAD)
A 3D graphical modeling of the butterfly valve’s disc components will be created using the computer program software, Computer Aided Design (CAD). In product and industrial design, CAD is used mainly for the creation of detailed 3D solid or surface models, or 2D vector-based drawings of physical components. Graphic representation is considered as one of the most important aspect in designing can be achieved through geometric modeling of mechanical parts in designing the butterfly valve’s disc components. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

3.2 Computer Aided Engineering (CAE)
Computer Aided Engineering (CAE) is the broad usage of computer software to aid in engineering analysis tasks. It includes Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). A CAE process comprises of preprocessing, solving, and post-processing steps. In the preprocessing phase, the model of the butterfly valve’s disc and the physical properties of the design, as well as the environment in the form of applied loads or constraints. The Finite Element Analysis application is a process of detecting, analyzing and finding the structural performance issues. The strength of the butterfly valve’s disc component plays an important role of controlling the flow of fluid in pipeline. Using the application of numerically and mathematically, FEM analyzed complex structural, fluid and variety of physical problems. A fluid flow through a design model in this case a butterfly valve’s disc needs to be analyzed using the application of Computational fluid dynamics (CFD) which was compromised with numerical analysis and algorithms for a result. The calculation that required to imitate the interaction of liquid and gases with surfaces defined by boundary conditions. This application will be an ideal method to analyze pressure differential of butterfly valve especially identifying the low pressure zone for each turning angle of butterfly valve. The cavitation index data will be plotted based on CFD analysis.

3.3 Computer Aided Manufacturing (CAM)
The Manufacturing process of the butterfly valve’s disc is based on the application of Computer-aided manufacturing (CAM) or commonly refer to the application of numerical control (NC) which used computational software to create the flow or instruction (G-code) that run computer numerical control (CNC) machine tools for manufacturing parts [8]. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object.

4. Results and Discussion
The butterfly valve was designed using the application of Computer Aided Design. Using CATIA, the detail design of the disc was constructed. The dimensions of the butterfly valve’s disc and shaft are based on the standard specified by the American Water Work Association. The butterfly valve with a diameter of 48 inch (1200 mm) has been selected as the reference size for analyzing the performance
of the valve using the application of computational aided. The diameter of shaft is also based on the minimum standard that had been specified by the American Water Works Association that is 82.6 mm.

4.1. Computer Aided Design (CAD)

The design of this particular butterfly disc is based on the sandwich theory but with a different “core” structure. Most sandwich materials used honeycomb shape as the core structure to increase the rigidity of the materials in the same time it is lightweight. Considering the drawback of honeycomb structure, which is expensive, a new design will be taken as consideration. An I-beam structure has a promising characteristic especially when considering the rigidity and toughness of the structure. I-beam structure acts as the important influence while designing the disc design [12]. Figure 5 shows how the influence of I-beam in the design. The I-beam sandwich structure will acts as the layer that support the main disc structure. Both I-beam sandwich structure and the disc acts as one component [4].

![Figure 5. Sandwich structure of the disc](image)

![Figure 6. Rectangular shaft](image)

The shaft of the disc was designed based on the rectangular cross-section. The cross length of the rectangle has the same diameter with the round cross-section shaft. The rectangular shaft design is to completely remove the keyways. Figure 6 illustrates the design of a rectangular cross-section shaft that will be connected with the disc. The connector that holds the shaft and the disc was designed to accommodate the structure operation. The connector design will affect the performance of the butterfly valve’s disc. One of the consideration that must be included is that the design of the connector must be based on the concept or a shape of an ‘aero foil’. The importance of this consideration is reduce the amount of drag force [10]. Figure 7 shows the flow of fluid during the fully open butterfly valve or 90° fully open valve.

![Figure 7. Flow of fluid at fully open valve](image)

![Figure 8. Connector](image)

The connector design must reduce the amount of drag force during the opening of a valve. Figure 8 is the detail design of the connector that attached the shaft and the disc. The eight holes appear on the part is to replace the pin on the shaft based on the design that already manufactured on today industry. The pin is replaced with a standard bolt to hold the disc and shaft together. Figure 9 and figure 10 picturized the fully assembled disc of a butterfly valve. The complete assembly was designed to meet the requirement of the standard design performance of perform a much better performance. This fully assembled will be analyzed structurally and fluid flow analysis under the application of computer aided engineering.
4.2. Computer Aided Engineering (CAE)

The application of computational aided engineering was applied to analyze the performance of the butterfly valve's disc, shaft and the connector. This is a crucial method to determine the reliability of the design. The application of computational aided engineering is separated into two section. The first section is to analyze the structure analysis using the understanding of finite element. The second section is to analyze the fluid flow of this butterfly valve inside a pipeline to measure the pressure differential for the cavitation index measurement. In this section, the structure analysis was performed to analyze the stress configuration on the structure. The material used for the butterfly valve is ASTM A108 standard based on American Water Works Association. The ASTM A108 materials standard specification for steel bar, carbon and alloy, cold finished. The upstream pressure inside the butterfly valve will create a distribution force acting on the surface of the disc. Based on the standard given by the American Water Works Association (AWWA), modern butterfly-valve designs for water service include cast-body construction in 25-psi (172-kPa), 75-psi (517-kPa), 150-psi (1,034-kPa), and 250-psi (1,723-kPa) pressure classes (Association, 2012). Using 172 kPa as an upstream pressure, the force acting on the surface of the disc of the butterfly valve. The maximum stress focus on the shaft, especially on the support. Based on this observation, the shaft suffer the most stress compare to the disc [13]. Figure 11, figure 12 and figure 13 show the stress and displacement result of the structure analysis.
The current disc then was analyzed for a comparison. Figure 14 shows the current design of the butterfly valve. The diameter and thickness of the disc is the same as the sandwich plate disc. The diameter of the shaft has the same hypotenuse length. Figure 15 shows the back view of the current disc structure. The one hole attached on the back of the disc is where the pin is positioned. The same distribution force applied on the surface of the disc.

Figures 14. Front view of improved design and Figure 15. Back view of the current design

The same boundary conditions was applied as the sandwich disc, the current disc was analyzed and the result of the stress configuration and the translational displacement was recorded. Figure 16 and figure 17 is the result of the stress configuration and figure 18 shows the translational displacement of the structure.

Figures 16. Current design stress analysis (front view) and Figure 17. Current design stress analysis (back view)
Figure 11, figure 12 and figure 13 show the result of the stress analysis of the sandwich disc butterfly disc. The figures represent the stress configuration and the displacement vector while figure 16, figure 17 and figure 18 represent the stress analysis and displacement vector for the current disc and shaft. From this evaluation, noting that the maximum stress on the current design is higher than the stress on the sandwich butterfly disc structure. The maximum stress concentrate on the shaft due to the fixed support based on the boundary condition that applied on the shaft. The stress configuration on the disc for both designs doesn’t suffer a great amount of pressure. However the displacement vector on the current design has the higher deflection due to the distribution force action on the surface of the disc. This can be justify that the disc deflects the most will allow more leakage during fully closed of the valve. From figure 17, the configuration stress on the pin section has a much higher stress concentration. This can be compared from figure 12 which the stress concentration on the bolt section is much lower. Table 2 is the comparison between the current disc design and the sandwich disc design.

|                          | Sandwich Design | Current Design |
|--------------------------|-----------------|---------------|
| Maximum stress (MPa)     | 117             | 365           |
| Stress at the Pin –(current)(MPa) | 39.2          | 153           |
| Stress at the bolt – (sandwich)(MPa) |                |               |
| Maximum Translational displacement (mm) | 2.16          | 5.04          |

Fluid analysis is conducted to observe the flow patterns and to measure pressure loss coefficient of this butterfly valve when the butterfly valve works with various opening positions [9]. The boundary condition of a pipeline was created to analyze the flow of fluid through the different opening of butterfly valve. The fluid medium that was used for this simulation is water with a density of 998 kg/m³. The valve opening is measured between 10° to 90° with an increment of 10° for each simulation. The properties used in this analysis is water with a constant temperature of 30°C. The vapor pressure on 30°C is 4.243 kPa. According to the specification of American Water Works Association, the maximum velocity through this valve cannot be more than 4.8768m/s. Hence, a uniform velocity of 4.8768m/s is imposed at the inlet boundary.
The data of the upstream pressure and downstream pressure was recorded on the table 3. The pressure differential was abruptly decrease based on the increasing of the opening angle between 10° to 40°. The pressure differential the decrease gradually from the valve opening between 50° to 90°. The upstream pressure then decrease whenever the opening of the valve is increase. This can be seen on table 3. The pressure differential that was analyzed based on the graph plotted on figure 21. The graph represent the pressure drop based on the positon of the opening of the valve.

### Table 3. Recorded data of each valve opening

| Valve opening | Upstream Pressure (pascal) | Downstream Pressure (pascal) | Pressure Differential (pascal) | Cavitation Index |
|---------------|----------------------------|------------------------------|---------------------------------|------------------|
| 10            | 623330                     | 232421.31                    | 390908.88                       | 1.58             |
| 20            | 439971                     | 253880.69                    | 186091                          | 2.34             |
| 30            | 337780                     | 220774.97                    | 117005.19                       | 2.85             |
| 40            | 256276                     | 197373.92                    | 58902.39                        | 4.27             |
| 50            | 221572                     | 178831.86                    | 42740.31                        | 5.08             |
| 60            | 201134                     | 182526.92                    | 18607.49                        | 10.58            |
| 70            | 190308                     | 182957.56                    | 7351.21                         | 25.31            |
| 80            | 184636                     | 178690.94                    | 5945.61                         | 30.34            |
| 90            | 184736                     | 182175.39                    | 2561.08                         | 70.47            |

The upstream and downstream pressure differential was used to analyze the cavitation index of the valve in each of the opening position. Using the reference of figure 4, the cavitation index performance was analyzed through plotting the graph on figure 22. Based on the graph plotted in figure 22 and the data from table 3, the performance of the valve can be estimate with the cavitation index based on the reference from figure 4. From the comparison, the cavitation index at the valve opening of 10°, 20° and 30° are in between the incipient and critical region. However the cavitation
index for that three opening positions are much closer to the incipient. Valve opening at 40° through 90° are above the incipient region. It means that the cavitation index is on safe operating zone. The opening at the incipient cavitation region typically does not cause damage or objectionably loud noise.

4.3. Computer Aided Manufacturing (CAM)

The butterfly valve’s disc model that was designed using the application of CAD. The file was save “STP” format for a compatibility towards the 3D printer. The purpose of CAM process is to analyze the structure in form of prototyping. The model was downscaled with a ratio of 1:16. Figure 23, figure 24 and figure 25 show the components of the butterfly valve.

![Figure 23. Disc prototype](image1)
![Figure 24. Connector prototype](image2)
![Figure 25. Shaft prototype](image3)

The 3D printer shows the materials used for fabricate the prototype. The materials used is a polylactic acid which can be fermented from crops such as maize. The 3D printer has no problem printing complex shape especially the sandwich layer. Moreover it is a fast and simple process when it comes to operation. Table 4 shows the time required to fabricate the parts and weight of the prototype respectively.

| Part     | Time (m) | Weight (g) |
|----------|----------|------------|
| Disc     | 29       | 5          |
| Shaft    | 100      | 17         |
| Connector| 19       | 3          |

5. Conclusion And Recommendation

The study has successfully shown that the application of CAD, CAE and CAM was able to design, analyze and fabricate the prototype of sandwich disc butterfly valve. The design of the valve structure has been modulated using the application of CAD. The design based on influences and considerations that will improved the performance of the structure. The application of CAE helps to analyse the stress concentration and the stress configuration region. A comparison analysis was done using the finite element to justify the performance of the structure. The second application of CAE is the computational fluid flow analysis. The upstream pressure and the downstream pressure was analysed to calculate the cavitation index and determine the performance throughout each opening position of the valve. The CAM process was done using rapid prototyping to produce a prototype and analysed the structure in form of prototype. The structure was fabricated based on the model designed initially through the application of CAD. The structure was downscale to fit the area required based on the specification of the 3D printer. The polyhedral mesh is a core volume mesh model that dictates the main aspects of the entire mesh to be constructed. Polyhedral cells created typically have an average of 14 cell faces and provide a balanced solution. A large advantage that the polyhedral meshing model has compared to tetrahedral meshes is that they are relatively easy and efficient to generate, and contain approximately five times fewer cells than a tetrahedral mesh, thus alleviating computational burdens. In order to properly apply computational fluid analysis, the pipe length downstream from the
installed butterfly valve must be long enough that the flow has become fully developed so as not to prematurely force the flow to a zero gradient condition.

6. References
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