Dynamic Torque Models for Quarter-Turn Air-Operated Valves

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Abstract

The U.S. nuclear power plants are currently developing and implementing air-operated valve (AOV) programs to ensure that safety-related as well as high-safety-significant valves will function reliably under their design basis conditions. The AOV population in the US nuclear power plants has several types of quarter-turn valves for which *validated* models are not available. Under Electric Power Research Institute's Motor-Operated Valve Performance Prediction Program (EPRI MOV PPP), validated models were developed for symmetric and single-offset butterfly valves; however, these models address only 2 out of more than 6 different types of quarter-turn valves used in AOV applications. Furthermore, these butterfly valve models that were developed for MOVs have been found to be overly conservative for AOVs, leading to unnecessary equipment modifications to address invalid operability concerns in many cases.

To address these issues generically and fill an important industry need, Kalsi Engineering, Inc. initiated a comprehensive program to develop validated models for quarter-turn valves in November 1999. The program includes development of first principle models, extensive computational fluid dynamics (CFD) analyses, and flow loop tests on all common types of AOV quarter-turn valves. The test program includes systematic evaluation of elbow orientations and proximities to quantify elbow effects on required torque. The program is conducted under a quality assurance program that meets 10CFR50 Appendix B requirements. The product of this program is a model report and supporting documentation that describes the methodologies and provides torque coefficient, flow coefficient, and elbow influence data.

The quarter-turn valve program results will benefit the utilities by providing reliable models for accurately predicting required torque for different types of AOVs; thus ensuring reliable operation while eliminating unnecessary and costly technical effort and equipment modification.

Introduction and Background

Problems with AOV operation can lead to safety concerns, reactor scrams, reduced plant efficiency, and increased maintenance cost [1, 2, 3]*. To address these issues and ensure that safety-related as well as highly safety-significant AOVs will function reliably under design basis conditions, the U.S. nuclear power plants are in the process of developing and implementing AOV programs. The Joint Owners Group for Air

* Numbers in brackets denote references listed at the end of this paper.

Operated Valves developed a document to provide programmatic guidance and recommendations to the utilities for their AOV programs. EPRI, in collaboration with four utilities, performed AOV design basis calculations under the EPRI pilot program. The methodology used in the pilot program for evaluating various types of valves is documented in Reference 7.

Implementation of the AOV evaluation methodology [7] and butterfly valve models developed under EPRI MOV PPP [5, 6] revealed two key issues for quarter-turn valves:

1. There are *no validated models* for several types of quarter-turn valves that constitute a large AOV population, and
2. EPRI MOV PPP methodology for symmetric and single-offset butterfly MOVs is based on a bounding approach that is *overly conservative*, and which in many cases leads to unjustified negative margin concerns in AOVs.

The first issue is due to the fact that the scope of the EPRI MOV PPP addressed only symmetric disc and single-offset butterfly valves because these cover a vast majority of the quarter-turn valve population in MOVs. However, far more variations exist in quarter-turn valves used in AOV applications (e.g., double-offset disc butterfly, spherical ball, partial ball, plug). Since there are no validated models for these common variations, industry is resorting to using "best available information" to determine torque requirements. Best available information includes data from technical publications for valve geometries that have significant differences in hydrodynamic characteristics (e.g., Refs. 10, 11), and manufacturers' sizing procedures (e.g., Refs 12, 13). Lessons learned during the MOV program to address USNRC's Generic Letter 89-10 concerns have shown this to be an unreliable approach.

The second issue is due to the fact that the EPRI MOV PPP used a *bounding approach* for the symmetric and single-offset butterfly valve models. These models were found to be satisfactory for MOV evaluations and benefited the utilities by eliminating the need for dynamic and periodic verification testing in many applications. However, the MOV actuators have generally higher output capabilities than their AOV counterparts, and their output is constant throughout the stroke. Consequently, excessive conservatism in the EPRI MOV PPM butterfly model over certain portions of the stroke imposes no significant penalty for MOVs. In contrast, the output from AOV actuators is typically lower and it varies significantly with stroke (e.g., Fig. 1). Therefore, excessive conservatism in the models can seriously penalize AOV evaluations resulting in invalid negative or low margin concerns in many cases.

Quarter-Turn Valve Model Development Program

Objectives

To fill the industry need, a comprehensive quarter-turn AOV model development program was initiated in November 1999. The objectives of the program are to

1. Develop improved models for symmetric and single-offset butterfly valves that accurately predict torque requirements and overcome limitations of the earlier models [5];
2. Develop torque prediction models for double-offset butterfly valves and other types of quarter-turn ball and plug valves that are commonly used in AOV applications at nuclear power plant.
3. Perform tests to support model development and validation. All tests must meet quality assurance requirements of 10CFR50 Appendix B.

Since upstream flow disturbances, e.g., elbows, can significantly influence the hydrodynamic torque [5], the models must include the effect of elbow orientation and proximity on the required torque.

Technical Approach

The key activities of the technical approach followed in the quarter-turn valve model development program are described below:

Population Survey

To determine which types of quarter-turn valves should be included in the program, a nuclear power utility survey was conducted. Survey data from 10 utilities that had categorized their valves based on the approach recommended by the AOV Joint Owners Group were evaluated. Results of the survey show that the six types of quarter-turn butterfly, ball, and plug valves shown in Table 1 cover more than 80% of the AOV population.

Cylindrical and tapered plug valves were given a low priority because they contribute less than 5% of the population

Analytical Models

Torque prediction models for the design variations shown in Table 1 were developed by rigorous application of first principles. Hydrodynamic torque exerted by the fluid flowing around the valve internals is a significant part of the total dynamic torque, and it is sensitive to disc geometry. Extensive computational fluid dynamics (CFD) analyses, as well as scale model flow tests satisfying the similitude requirements, were performed to accurately quantify the hydrodynamic torque on the discs of different shapes.

For butterfly valves, disc geometries included are symmetric, single-offset, and double-offset. The maximum thickness at the center of the butterfly valve discs can vary significantly depending upon the valve size and pressure class. An earlier survey [6] had shown that variations in the ratio of disc thickness to disc outside diameter (also called disc aspect ratio) from 0.15 to 0.35 cover the vast majority of nuclear power plant applications.

The model development approach includes full spherical ball, segmented ball (also called partial ball or V-Ball), and an eccentric plug (also called Camflex) valve designs. For ball valves, the ratio of spherical ball diameter to mean seat diameter is relatively constant for pressure classes ranging from ANSI 150 through ANSI 1500. This is because the minimum spherical diameter necessary for sealing is geometrically related to the mean seat diameter; the resulting strength of the full spherical ball structure is adequate to handle differential pressures up to ANSI 1500 for commonly used materials.

Our review of the recently published ball valve model [8] for AOV/MOV predictions shows that data from an earlier scaled model test performed on a *ribbed* ball valve [10] were used to predict hydrodynamic torque on *full spherical* ball designs (Figs. 2A, 2B). It should be noted that, to save weight, the ball closure element in large ball valves is typically a ribbed structure (which has sufficient strength to handle the ΔP and operating loads) instead of a full spherical ball structure. The ribbed spherical ball designs are commonly used in large pipelines and hydroelectric power plants, but not in fossil or nuclear power plants. When a ribbed ball is partially open, the flowing fluid exerts forces on both the outside rib structure and the inside flow path in the ball (Figs. 2, 3). Accordingly, the hydrodynamic performance of a ribbed ball design is not applicable to a full spherical ball design because of these gross differences in geometries and flow patterns. Our model development included flow loop testing of a full spherical ball design to overcome this deficiency.

CFD Analyses. Extensive 2-D and 3-D coupled fluid structure analyses were performed to support the development of ball, plug, and butterfly valve models (e.g., Figs 3, 4). Figure 4 shows the details of a 3-D CFD model of a symmetric disc butterfly valve used to improve accuracy over the earlier validated models [5], which were based on approximate solution using 2-D streamline functions [9]. To obtain reliable solutions by CFD, the current state-of-the-art requires the user to have an in-depth fundamental understanding of the approaches used in the analysis codes, including their applicability and limitations [14]. Both the fluid domain and the butterfly disc structure were discretized to obtain flow velocities and pressure distributions as well as the resultant force and torque on the disc. The stability and convergence of the solutions were confirmed by performing a sufficiently large number of iterations and evaluating the resultant key parameters of interest, i.e., torque, ΔP, valve resistance coefficient, K_v, and the torque coefficient, C_t, as shown in Figure 5. The analytical predictions were validated against test results as discussed later in this paper.

Flow Loop Testing

The model development effort included extensive flow loop testing (Fig. 6). The test specimen matrix covered the six types of valve geometries shown in Table 1. The key objective of these tests was to accurately determine hydrodynamic torque coefficients and flow coefficients (or valve resistance coefficients) for each valve geometry under baseline conditions as well as in the presence of upstream elbows.

Test valves and the flow loop were instrumented with a digital data acquisition system to measure and record the following parameters:

- Flow rate
- ΔP across the test valve section
- Upstream pressure
- Downstream pressure
- Stem torque
- Disc position

Detailed procedures were developed for test specimen inspection, assembly, testing, data reduction, and data plotting. The procedures follow the same approach as the one pursued earlier for butterfly valves [4], which had the benefit of independent design review and input from the EPRI MOV PPP Technical Advisory Group utility members.

For each valve, the test matrix includes:

- Baseline tests consisting of 18 static and dynamic strokes (Table 2)
- Dynamic strokes under 3 ΔPs and 2 flow rates to verify nondimensionality of torque and flow coefficients.
- Tests in both flow directions for nonsymmetric valves (i.e., segmented ball, Camflex plug, single-offset butterfly and double offset butterfly), and
- Effect of upstream elbows with 3 orientations and several elbow proximities ranging from 0 to 20 pipe diameters.

Test data from various tests are reduced and compared to ensure data accuracy, repeatability, and reliability, and to develop torque and flow coefficients (C_t, C_v) in both flow directions, and torque multiplying factors (C_{up}) for the elbow influence.

All tests were performed on 6" nominal size valves. Applicability of the nondimensional torque and flow coefficients and models to larger size valves was previously validated by performing full-scale tests on a 42" butterfly valve [4].

Test procedures and the flow loop set-up were streamlined to allow an efficient evaluation of other valve geometries that are not covered by the current test matrix.

Test Results

Figure 7 shows typical measured raw torque data and averaged torque data (per degree) for an opening and closing stroke of a full ball valve. These data are used to calculate hydrodynamic torque and friction torque components using procedures described in Refs. 5, 6. The nondimensional torque coefficient, C_t, as a function of disc opening angle for a full spherical ball from different maximum ΔP tests, is shown in Figure 8A. The results from different tests overlap well, confirming the nondimensionality of C_t.

Figure 8B shows C_t results for a partial ball (nonsymmetric design) in both flow directions. The differences in torque coefficients in the two directions are very significant. This shows that torque requirements in both directions under various plant conditions as well as design basis conditions need to be appropriately considered to ensure that the valve will perform its function under all applicable scenarios. It is noted that the manufacturers' sizing equations (e.g., Ref. 13) do not address both flow directions.

The results of elbow tests show that the magnitude of the elbow effect on the torque requirements for quarter-turn ball valves of different shapes is quite different from that found for the butterfly valves [4, 5, 6]. Accordingly, the elbow effect models for full ball, partial ball, and eccentric plug valves are different from those for the butterfly valves.

Model reports for each valve fully document analytical methodologies, torque coefficients, C_t, flow coefficients, C_v, and the peak torque ratio factors, C_{up}, for different upstream elbow orientations and proximities.

Validation of CFD Predictions

Figure 9 shows a comparison of the CFD predictions against test data of a symmetric disc butterfly valve torque coefficients, C_t, and valve resistance coefficients, K_v. The good agreement provided the basis for more accurate torque prediction models for butterfly valves.

Example of Model Application

Figure 10 shows a comparison of torque requirements for a 16" symmetric disc butterfly valve in a service water application based upon the earlier model [5, 6] and the more accurate model developed under the new program. The predictions are for the same bearing friction coefficient and other operating parameters. As seen, the new model revealed an adequate margin for this AOV in contrast to the negative margin predicted by the MOV PPM. This major benefit is due to the improved quantification of the hydrodynamic torque component. It should be emphasized that, unlike friction coefficients, the hydrodynamic torque component is constant for a given geometry and operating conditions and is not subject to degradation. Therefore, more accurate hydrodynamic models provide major benefits in AOV evaluations, and this benefit is particularly dramatic for large valve sizes.

QUALITY ASSURANCE

All testing and model development activities were conducted in accordance with a quality assurance program that satisfies 10CFR50 Appendix B requirements .

CONCLUSIONS

1. Accurate models for symmetric and single-offset butterfly valves have been developed that can be used to reliably predict torque requirements without the excessive conservatism of earlier models.

2. Additional models for double-offset butterfly valve, full ball valve, partial ball valve, and eccentric plug (Camflex) valve resulting from this program fill the industry need for reliable design basis calculations for quarter-turn AOVs without excessive conservatism.
3. These models eliminate the potential for unwarranted operability concerns and unnecessary equipment modifications, thus increasing plant availability and ensuring reliable operation of AOVs.

To facilitate efficient use of the models for AOV evaluations and design basis calculations, the methodologies and flow, torque, and elbow influence coefficients have been incorporated into a user-friendly software.

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* EPRI proprietary reports available to participating utilities.

Item	Type	Description
1	Butterfly	Symmetric disc
2	Butterfly	Single-offset disc
3	Butterfly	Double offset disc
4	Ball	Full spherical ball valve (both floating and trunnion mounted designs)
5	Ball	Segmented (also called partial or V-notch) ball valve
6	Plug	Eccentric plug (also called Camflex) valve

Note: The test matrix includes cylindrical and tapered plug valves at lower priority.

Table 1: Types of Quarter-Turn Valves Covered by the Program

Stroke	***Description***	***Direction***	***Flow (% Nominal)***	***Pressure (% Max.)***	***ΔP (% Max.)***
Pre-Test Packing Friction					
1	Static Test	O → C	0	0	0
2	Static Test	C → O	0	0	0
3	Static Test	O → C	0	100	0
4	Static Test	C → O	0	100	0
Bearing Checkout Test					
5	Bearing Torque (thrust) Test	C →10° O	Any	100	100
6	Bearing Torque (thrust) Test	10° O →C	Any	100	100
Flow and ΔP Parametric Tests					
7	Flow and ΔP	O → C	100	100	100
8	Flow and ΔP	C → O	100	100	100
9	Flow and ΔP	O → C	100	67	67
10	Flow and ΔP	C → O	100	67	67
11	Flow and ΔP	O → C	100	33	33
12	Flow and ΔP	C → O	100	33	33
13	Flow and ΔP	O → C	200	100	100
14	Flow and ΔP	C → O	200	100	100
Post-Test Packing Friction					
15	Static Test	O → C	0	0	0
16	Static Test	C → O	0	0	0
17	Static Test	O → C	0	100	0
18	Static Test	C → O	0	100	0

Notes: 1. Nominal flow velocity is 15 fps.
2. Maximum ΔP is 90 psi (nominal).

Table 2: Description of Typical Test Sequence for Baseline and Elbow Tests

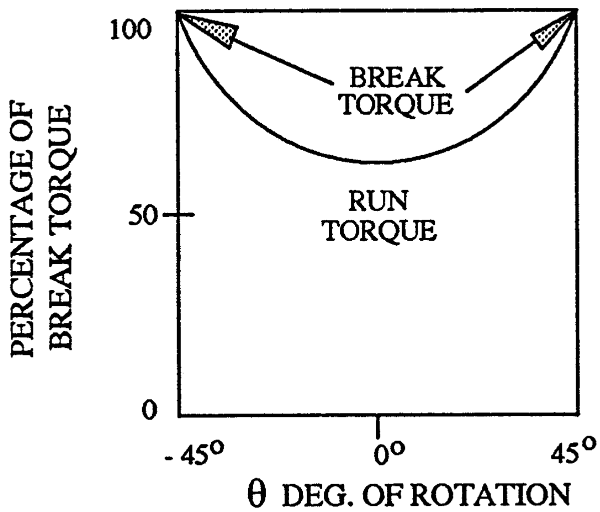
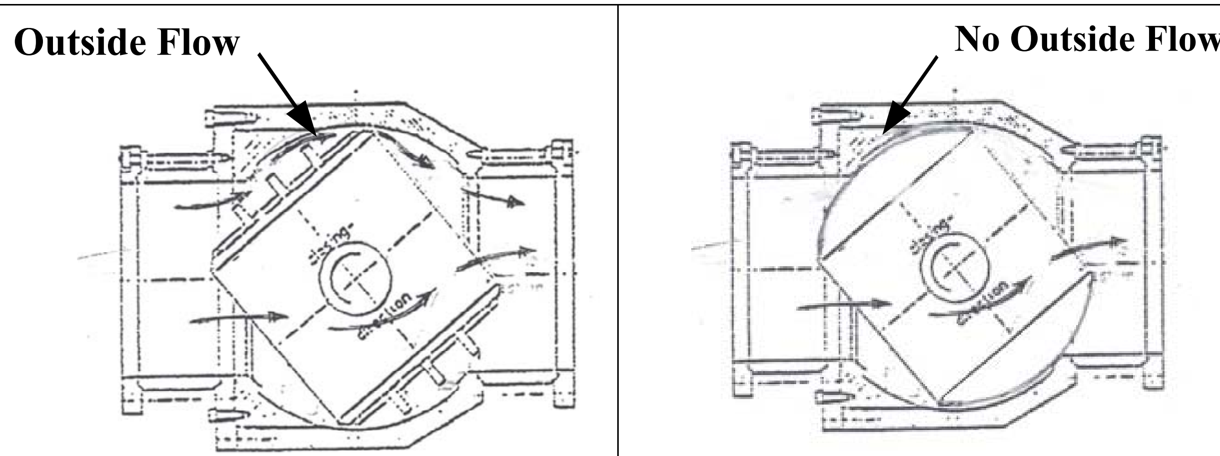


Figure 1

Torque Output Varies Significantly with Stroke for Quarter-Turn AOV Actuators

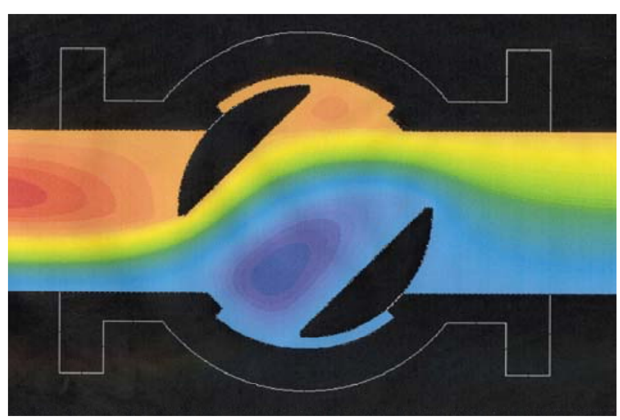


2(A): Ribbed Ball

2(B): Full Ball

Figure 2: Geometry differences between the ribbed spherical ball [10] and full spherical ball designs significantly influence their hydrodynamic performance.

Figure 3
Typical CFD Analysis of a Full Ball/Plug Valve



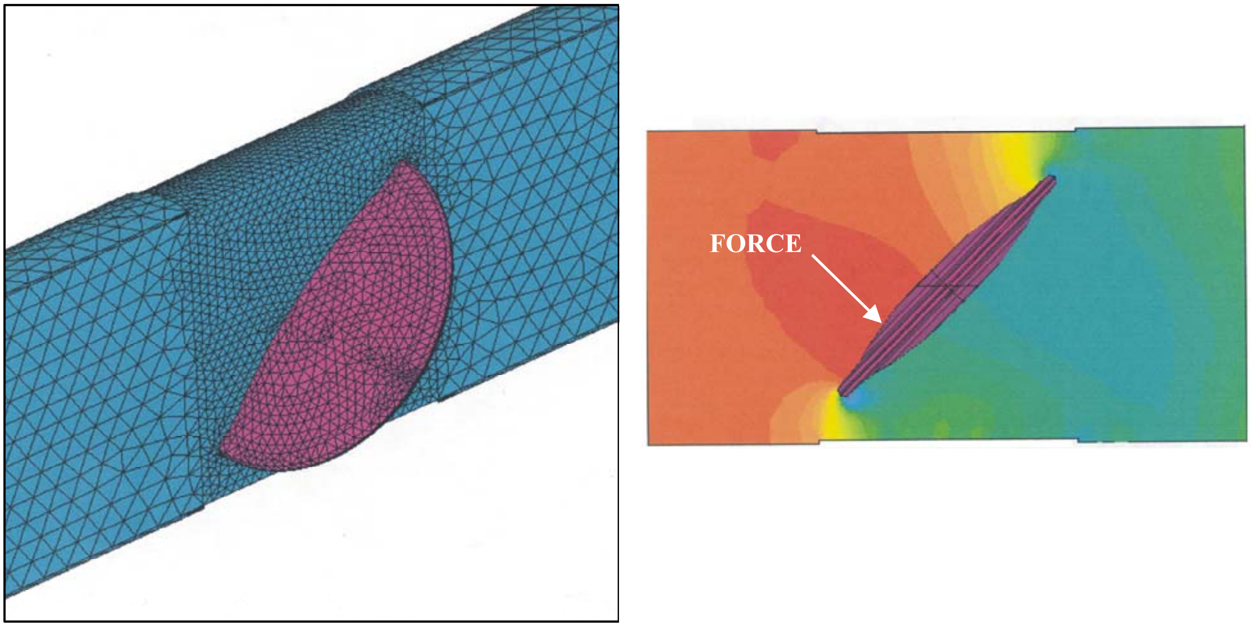


Figure 4
3-D CFD Model and Pressure Distributions for a Symmetric Disc Butterfly Valve

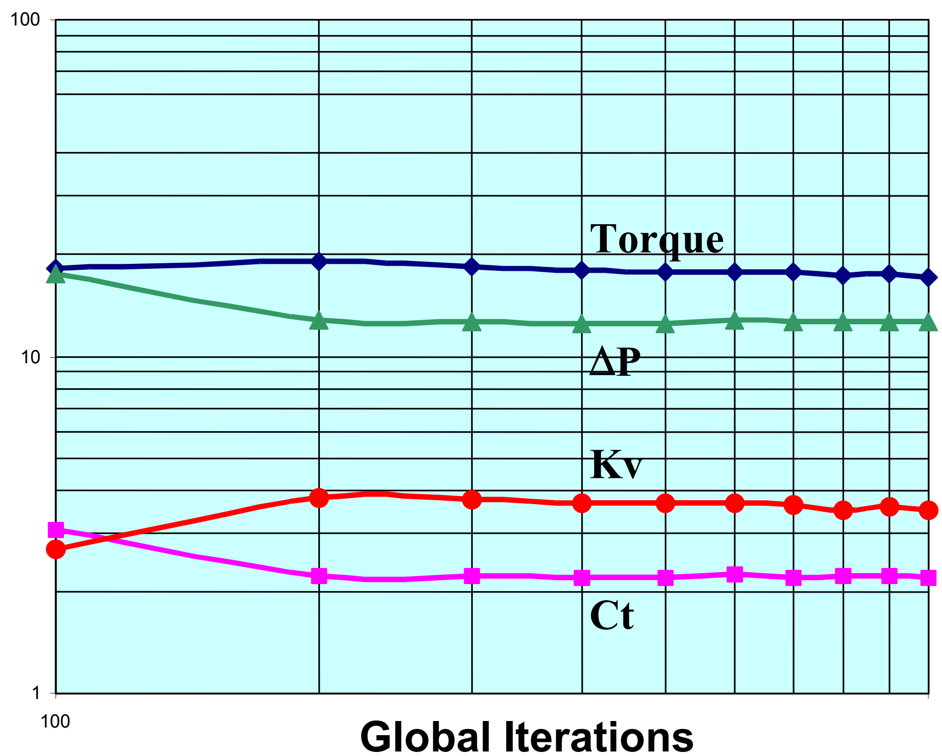


Figure 5
Stability and Convergence of CFD Solutions Confirmed by a Large Number of Iterations

Figure 6
Flow Loop Testing of a Spherical Ball Valve with an Upstream Elbow In Progress

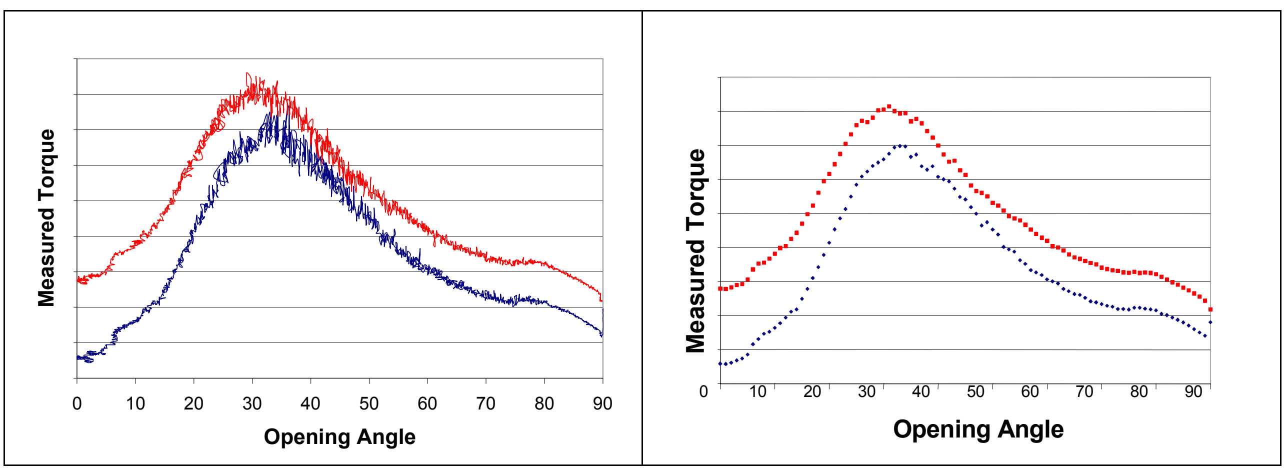
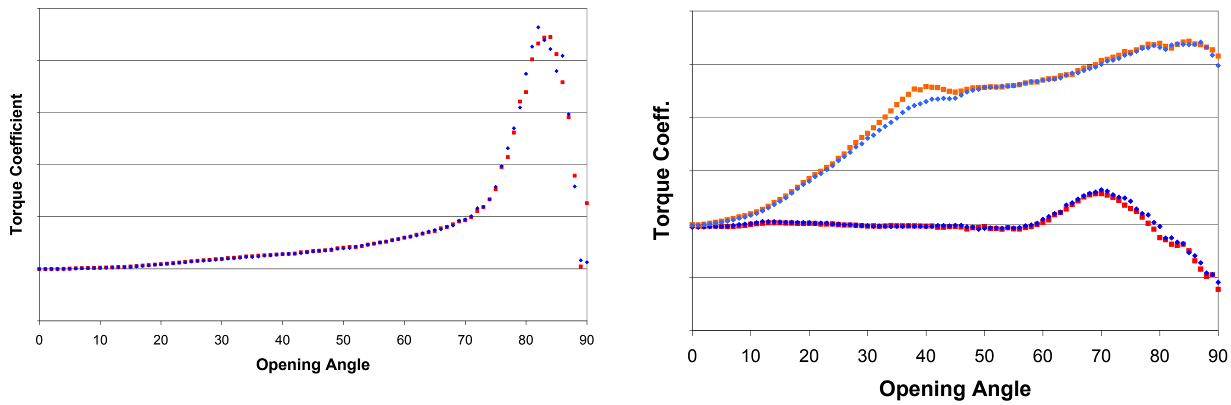


Figure 7
Typical Raw Data and Average Data (for each degree increment) for an Opening and Closing Stroke of a Full Ball Valve



8(A) **8(B)**

Figure 8
Typical Torque Coefficients for (A) Full Ball and (B) Partial Ball Valves

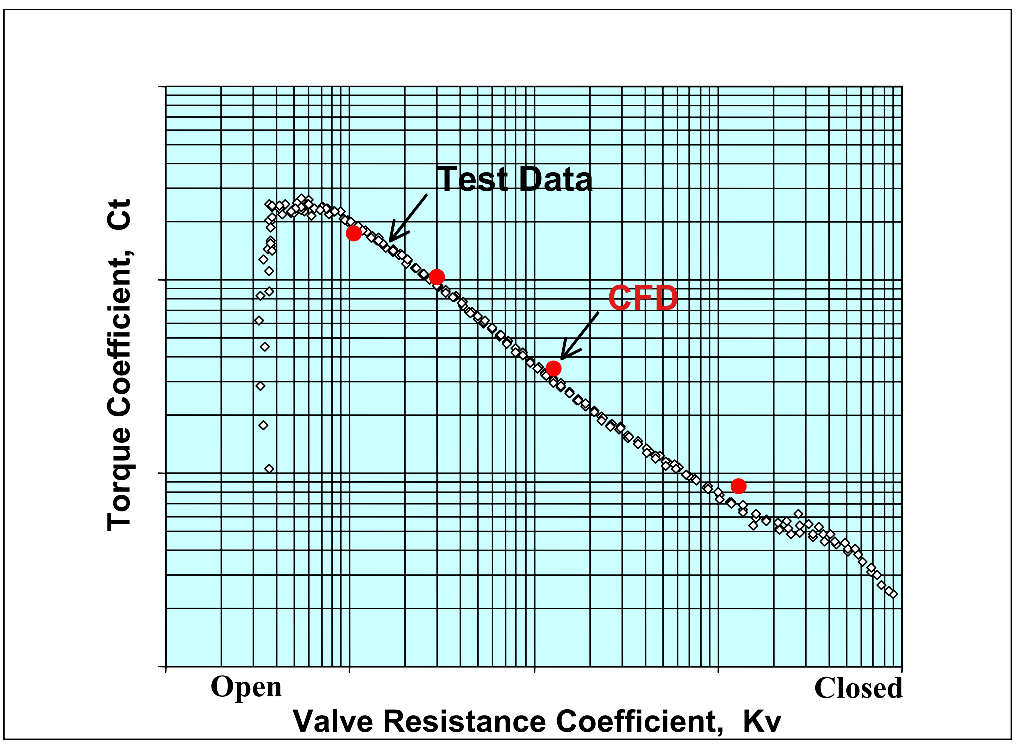


Figure 9
CFD Predictions for a Symmetric Disc Butterfly Valve Validated Against Test Data

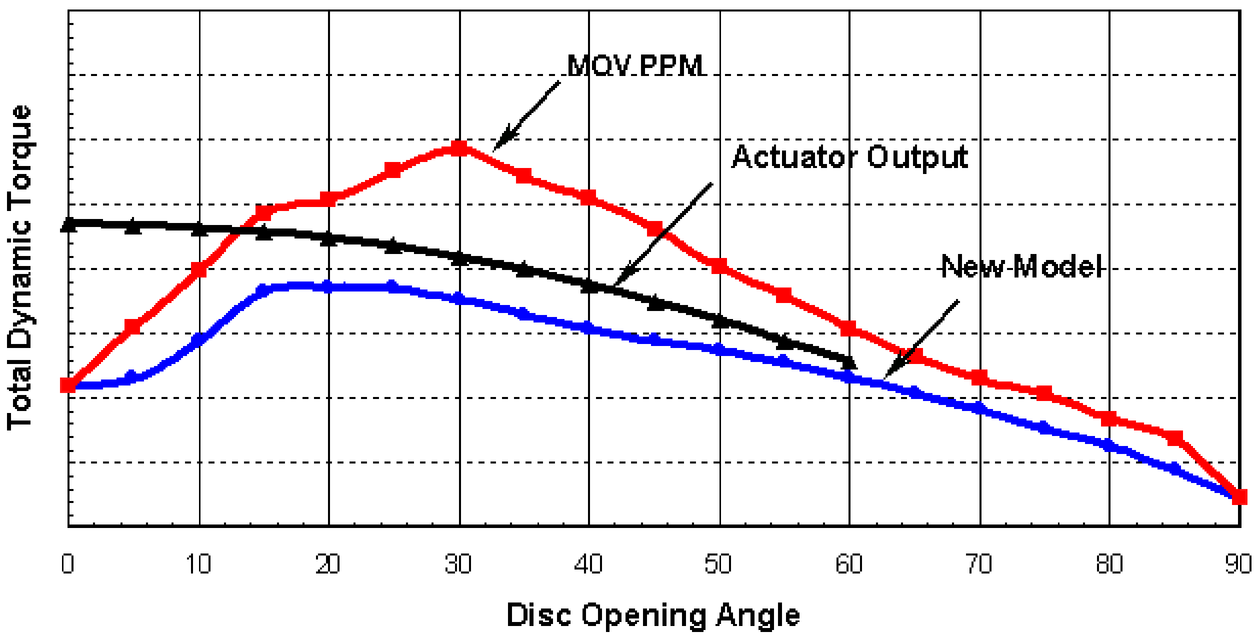


Figure 10
New Butterfly Valve Models Eliminated Need for Modifications while
Ensuring Reliable Operation of 16" Butterfly Valves