

Design and Testing of Actuator for Butterfly Valve

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Abstract

This paper presents the theory for design of Worm and Worm Wheel Actuator for the Butterfly Valve. The design of actuator is totally based on the operating torque value of the valve. The worm gear pair is dominant over other gear pairs because of its unique properties. The worm and worm wheel gears are used to obtain large gear ratios. It offers large speed reductions hence gives increased output torque. Because of this property, worm and worm wheel gearboxes are used as actuators of the valves where high torque values are required. For manual operation, the worm gear is most suitable, but the design must compensate for manual inconsistency. The gear pair is designed for 5000 Nm. of torque. Testing is carried out directly on the butterfly valve. Supplied torque values are measured directly by using Dial Type Torque Wrench. The test results are compared with design data and conclusion is drawn.

Keywords: Butterfly Valve, Torque, Worm Gear.

Introduction:

The butterfly valve is well known for flow control with Class IV leakage. It consists of a body, disc, stem or shaft and a rubber seal. The operation of this valve is as; the disc with rubber seal mounted on its periphery rotates in the body with the help of shaft and closes the flow. The disc rotates only for 90° from open to close position or vice versa. The power to open or close is provided through the shaft. The valve actuator is mounted on the body which rotates the shaft and the disc. For developing an actuator, the power i.e. torque to be applied on the shaft must be known. As Butterfly valves are of double eccentric type, one of the torque values i.e. for opening or closing the valve is larger than other, depending on the side of eccentricity. [3]

There are various mechanisms available for the actuation of the butterfly valves. But in the most common applications, valves are actuated manually with the help of worm gear. The worm gear drive consists of a worm and worm wheel. The teeth on

the worm wheel envelop threads on the worm and give line contact between mating parts. The advantage of the worm gear drive is their high speed reduction. A speed reduction of as high as 100:1 can be obtained with a single pair of the worm gears. The very important advantage which makes a worm gear pair useful for actuating valves is its self locking property. The worm gear can transmit power in one direction i.e. from worm to worm wheel only and doesn't give any response to the power received from worm wheel. This makes the valve disc to remain at set position and doesn't allow it to move because of dynamic forces applied by flowing fluid.

Design of gear box:

The gear box consists of a worm and a segment of worm wheel. The other parts are as; body, cover, shaft, hand wheel, dowel pins, thrust bearings, 'O'-rings, studs and fasteners. The design process starts from worm gear pair. As there is only one criterion for selecting the worm gear pair i.e. output torque, the selection is carried out on the basis of trial and error method with respect to the factor of safety. The selection of transmission ratio of standard gear pair is based on the output torque required and the input torque supplied by the human operator. The input torque is human effort multiplied by the radius of hand wheel. These three values of transmission ratio, human effort and hand wheel diameter are selected such as the output torque value will match the requirement. This process of selecting these values is totally based on the experience. In this work, the output torque value selected is 5000Nm. which is input torque required for the butterfly valve of size 700 MM operating at PN 10 pressure rating.

At first, selected the gear pair 1/52/10/4 from I.S. 3734-1966, (Dimensions of worm gearing). After carrying all analytical tests on this gear pair, it is found that the factor of safety is below 1, which is not permissible. Therefore selected next pair with bigger dimensions for better strength is 1/54/10/5 with centre distance of 160 MM. The other dimensions are calculated as follow: [1, 2]

Worm:

$$d_1 = q * m = 10 * 5 = 50 \text{ mm} \quad (1)$$

$$d_{a1} = m(q + 2) = 4(10 + 2) = 48 \text{ mm} \quad (2)$$

$$\tan \gamma = \frac{Z_1}{q} = \frac{1}{10} \quad (3)$$

$$\gamma = 5.71^\circ$$

$$d_{f1} = m(q + 2 - 4.4 \cos \gamma) = 38.1092 \text{ mm} \quad (4)$$

$$P_x = \pi * m = 15.7080 \text{ mm} \quad (5)$$

Worm Wheel:

$$d_2 = m * Z_2 = 270 \text{ mm} \quad (6)$$

$$d_{a2} = m(Z_2 + 4 \cos \gamma - 2) = 279.9 \text{ mm} \quad (7)$$

$$d_{f2} = m(Z_2 - 2 - 0.4 \cos \gamma) = 258.01 \text{ mm} \quad (8)$$

$$F = 2 * m * \sqrt{q + 1} = 33.16 \text{ mm} = 35 \text{ mm} \quad (9)$$

$$C = 0.2 * m * \cos \gamma = 0.9950 \text{ mm} \quad (10)$$

Force analysis:

The input torque is applied force by human operator multiplied by handwheel radius. The human can easily apply the force of 60-80 Kg., selecting the force of 60 Kg. and handwheel of 600 MM diameter. With respect to these values, the input to the gearbox will be 176.5 Nm. The various forces introducing in the gear while transmitting the force to the valve are calculated as follow; [1, 2]

We have $\alpha = 20^\circ$, $\mu = 5.71^\circ$.

$$\text{Rubbing Speed } v_s = \frac{\mu * d_1 * n_1}{60000 * \cos \gamma} = 0.1579 \text{ m/s} \quad (11)$$

From Rubbing Speed vs. Coefficient of friction diagram, for $v_s = 0.15 \text{ m/s}$ $\mu = 0.07$

$$(P_1)_t = \frac{2 * M_t}{d_1} = 7063.20 \text{ Nm} \quad (12)$$

$$(P_1)_a = (P_1)_t * \frac{(\cos \alpha * \cos \gamma - \mu \sin \gamma)}{(\cos \alpha * \sin \gamma + \mu \cos \gamma)} = 40167.62 \text{ N} \quad (13)$$

$$\text{As } (P_1)_a = (P_2)_t$$

$$\text{Therefore, } (P_2)_t = 40167.62 \text{ N}$$

$$M_{t_2} = \frac{d_2}{2} * (P_2)_t = 5422.62 \text{ Nm} \quad (14)$$

$$(P_1)_r = (P_1)_t * \frac{\sin \alpha}{(\cos \alpha * \sin \gamma + \mu \cos \gamma)} = 14806.46 \text{ N} \quad (15)$$

$$\text{As } (P_1)_r = (P_2)_r$$

$$(P_2)_r = 14806.46 \text{ N}$$

Strength analysis of gear pair:

As, the teeth of worm wheel are weaker than the teeth of worm, therefore it is necessary to check the design on the basis of bending strength of tooth of worm wheel, the factor of safety against bending is given by, [4]

$$S_b = \frac{\sigma_{lim}}{\sigma_{max}} \quad (16)$$

Where

σ_{lim} = Limit stress of gear tooth.

The tooth of the gear is subjected to the fluctuating bending stress as it comes in contact with the meshing tooth. As teeth are subjected to the fluctuating stresses, endurance limit stress is the criteria of design. Therefore the maximum bending stress is equal to the endurance limit stress of the gear tooth. Earle Buckingham has suggested that endurance limit stress of the gear tooth is approximately one-third of the ultimate tensile strength of the material therefore,

$$\sigma_{lim} = \frac{1}{3} S_{ut} \quad (17)$$

And

$$\sigma_{max} = \frac{(P_2)_t}{\pi * m * F} \quad (18)$$

Material selection:

The threads of the worm wheel are subjected to the fluctuating stresses and the number of stress cycles is fairly large. The core of the worm should be kept ductile and tough to ensure maximum energy absorption. The worms are, therefore, made of case hardened steel with a surface hardness of 60 HRC and case depth of 0.75 to 4.5 mm. The normalized carbon steel (40C8) is most common used material with $S_{ut}=580-680 \text{ N/mm}^2$ and $S_{yt}=320 \text{ N/mm}^2$. [1,4]

The magnitude of contact stresses on the worm wheel teeth is the same as on the worm threads, but the number of stress cycles is reduced by the factor equal to speed reduction. The worm wheel can't be accurately generated in the hobbing process. The final profile and finish of the worm wheel teeth is the result of plastic deformation during the machining process. Therefore the worm wheel material should be soft and conformable. The material should possess hardness between 90 – 120 BHN. The Spheroidal Graphite Iron grade 65-45-12 is best suitable and easily available material that can be used with the properties given in following table.

Table: Mechanical Properties of Worm Wheel Material

Mechanical Properties	ASTM A536 GRADE 65-45-12
Tensile strength	448 MPa
Yield strength	310 MPa
Elongation in 50 mm	12 %
Hardness	200 BHN

Therefore, from equation 17 & 18;

$$\sigma_{lim} = \frac{1}{3} S_{ut} = 149.33 \text{ N/mm}^2$$

$$\sigma_{max} = \frac{(P_2)_t}{\pi * m * F} = 71.09 \text{ N/mm}^2$$

Therefore, from equation 16;

$$S_b = \frac{149.33}{71.09} = 2.1$$

As the factor of safety is 2.1, there is no any chance of breaking of worm wheel tooth as no large power is to be applied to open or close the valve (60 kg effort); also no extra force is expected from operator. [2]

Testing of the gear box:

This gear box will be used for actuating the Butterfly Valve. Before putting gear box to the application, the testing of it is must. The criterion is the strength only, i.e. this gear box must work properly without failure for rated torque. The efficiency and gear related aspects of gear box don't have importance here as it is a manual operated gear

box. Therefore for testing, it would be better if gear box is applied to its actual working conditions.

Testing Process:

The gear box is coupled with the shaft of 700 MM Butterfly Valve at the top flange. The shaft is engaged with the hub by sunk key. The gear box is tightened on the top flange using studs and nuts. The valve is then clamped on the testing rig with valve disc in partially open position. The valve is completely filled with water, close the disc insuring that no air is entrapped in the valve and pressure is applied.

The reading is taken with the help of Dial Type Torque Wrench having range of 20-200Nm. This torque wrench is fitted on the input shaft of gear box replacing the handwheel. The force is applied by the operator directly on the torque wrench and valve is opened. Torque wrench gives the reading of torque supplied to the input shaft.



Fig.: Testing Setup

Test Results:

The torque supplied by the gear box to the valve is calculated by multiplying the obtained reading with mechanical advantage of gear pair. As the gear box is designed to work easily at rated pressure, but it will be better to check its performance with increasing pressure from zero to rated. Following chart shows the pressure applied and torque value applied by the gear box.

The gear pair is designed with factor of safety of 2.1. During testing the gear box is applied to load of 1.5 times the rated load. After testing, the gearbox is disassembled and all parts are checked for any failure like cracks, bend and wear. No any type failure is obtained on any part of the gear box. This ensures proper functioning of gear box for rated output of 5000 Nm. without failure.



Fig.: Measurement of Torque

Table: Test Results

Sr. No.	Pressure in Kg/cm ²	Applied Torque Nm
1	6	3480
2	10	4500
3	12	5880
4	16	7840

Conclusion:

The worm gear pair as actuator has its own advantages over other gear pairs. The worm gear box can be easily coupled with any power source like electric motor because of no any reverse action. Testing proved that selected gear pair has given better performance, also has ensured the interrupted functioning for conditions to which it is to be applied while working on site.

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