**Proceedings of ICFDP 8:**
**Eighth International Congress of Fluid Dynamics & Propulsion**
**December 14-17, 2006, Sharm El-Shiekh, Sinai, Egypt**

ion

**ICFDP8-EG-124**

# Designing a Test Rig for Radial Hydrodynamic Disc Seal (HDS)

Bijan. Farhanieh
Professor of
Mechanical Engineering

Mohammad Durali
Professor of
Mechanical Engineering

Abbas Tourani
M.Sc. student of
Mechanical Engineering

Sharif University of Technology
Department of Mechanical Engineering
Tehran-Iran
E-mail:tourani@techstudies.org

**Abstract:**
For sealing in high speed turbo pumps due to high-speed rotation, a special seal is used. This type of sealing, works similar to centrifugal pumps. It gives energy to leakage fluid and returns the fluid to pump's flow cycle. Sometimes this sealing is used in bearing cooling system.
Thus it is important to be sure about sealing device before applying in turbo pump unit. Therefore, test rig is one of the most important apparatus in high-speed turbo pumps research centers.
In this project, first a study about this sealing system is done and then refers to this study, method & procedure of the tests has been gotten. Also according to design standards Test rig has been designed.

**Key words:**
1- Sealing disc, 2- radial hydrodynamic, 3- turbo pumps, 4- high-speed, 5- non-contact seal

## Nomenclature

a: radius of disc (L)
b: radius of wall or width of disc (L)
c: radial clearance between disc and housing (L)
$s_s$: axial clearance between smooth side of disc and housing (L)
Sv: axial clearance between vaned side of disc and housing (top of vane) (L)
r: radius (L)
$c_m$: dimensionless torque coefficient, Cm=M/(0.5*w2R5)
p: pressure ($F/L^2$)
Q: Volumetric flow rate (L3/T)
u: absolute tangential velocity component (L/T)
Re: Reynolds number
X: engagement ratio,(a-r)/a
K: velocity ratio
β:angular velocity of fluid core(1/T)
ω:angular velocity of disc(1/T)
ρ= density (M/L3)

## Introduction

Statistical investigation shows that about 60% of weak points in turbo pumps engines are due to weakness in seals [5].And hydrodynamic disc seal (HDS) is the one of the important parts of seal system in high speed turbo pumps. Because of its essential role in turbo pump, it should be tested individually. Prelude to this investigation, is an analysis of theory and doing some laboratory examination. With processing of this information the specification of the Hydrodynamic Disc Seal (HDS) and its parameters will be obtained. And the confidence about correctly working of the sealing system before assembling it on turbo pump will be attained.

In this paper, method and result of designing a test rig has presented. As most of readers, don't know about HDS, so first of all, HDS are introduced. Advantage and disadvantage of HDS has explained and described brief equation and theory. After that, test procedure and design steps are discussed.

## Kind of seals

Turbo pump usually have two pumps. These pumps deliver poison working fluid in corrosion environment. Therefore leakage loss from these working fluids is one of the most important issues in turbo pumps.

Turbo pump sealing device usually have been divided in two groups.
1- Contact sealing: to seal with fitting leakage devices between flow areas. These sealing couldn't work at high pressure for a long time. Erosion phenomena happen in interface between shaft & sealing devices. Therefore a little quantity of leakage should be streamed to increase life time of contact sealing.
2- Non-contact sealing: this type of sealing does not fill space between working fluid and geometry body completely and only decrease this space.

**HDS Applications**

Application of this seal is concentrated in the areas of high speed and/or corrosive environment. In addition to Ref. 1, 3, 5 they are used in a rocket engine, chemical process industry. Axial non contact seal (labyrinth) and radial (disc seal) are used in turbo pumps.
It's evidence that in statically conditions, this kind of seal doesn't work. Also in rotational speed less than nominal speed again doesn't work. Therefore always work with statically sealing devices.

**How HDS work**

Hydrodynamic Disc Seal works as a pump impeller in centrifugal pumps. (Fig1) a disc mounted on a shaft which is surrounded with a moderately closed fitting housing which usually has plane, smooth end walls.

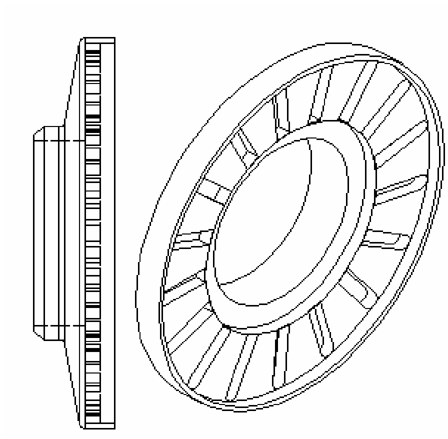

Fig (1): Hydrodynamic Disc Seal

The disc includes one smooth side or mostly smooth while the other side carries vanes or grooves. When the housing has been filled with liquid and the shaft is being rotated, the disc's drag force causes the liquid to rotate and thus a radial pressure gradient is produced. But because of the vanes, the liquid on this side of the disc has a greater mean tangential velocity and hence a steeper radial pressure gradient. Therefore the pressure p will be greater than p0 and a net pressure difference will be generated.
If P0, the pressure of the gas which is admitted to the vaned side of the seal, then for a specific range of P/P0 ratios a cylindrical free surface will form on that side of the seal. For P0 equal to atmospheric pressure the seal will be self regulating for values of P varying from substantially above atmospheric to slightly below atmospheric. [1]
Hydrodynamic disc seals are investigated experimentally and theoretically. In 1958 Daily and his assistant at MIT university hydrodynamic laboratory, showed four regimes of flow around disc which is surrounded with a moderately closed fitting housing. [3] Those showed that these regimes depend on the Reynolds number (Re) and aspect ratio(s/a). In each regimes a specific function of Reynolds number and aspect ratio(s/a) are entered for pressure coefficient and torque coefficient,. (FIG2&3)
The following theory that is going to be mentioned was presented by Ketola and includes each of four regimes. [2]

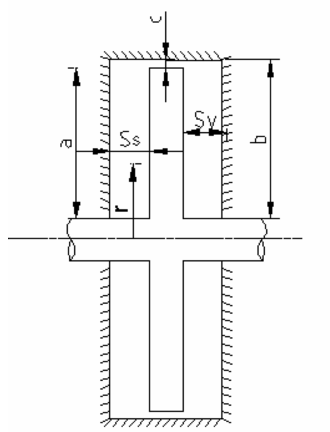


Fig (2): HDS in chamber

**Ketola Theory**

As followed, a brief describe of this theory are presented. Full explanation of that is in reference [2]. Results of this theory are mentioned in the table (1). In this theory, for each regime in figure (3), assume some suppose and separate equation for torque coefficient has gotten.
First regime: laminar flow, merged boundary layers
Second regime: laminar flow, separate boundary layers
Third regime: turbulence flow, merged boundary layers
Fourth regime: turbulence flow, separate boundary layers

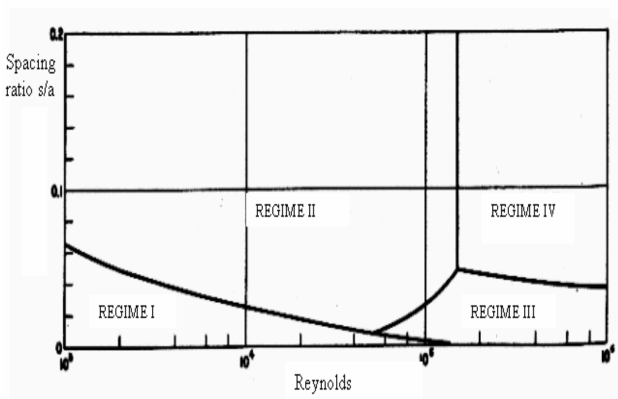

Fig (3): flow regimes for HDS in chamber

Table (1): Ketola theory results

| Equation | Flow regimes |
|---|---|
| $C_m = \pi C_3 /((s/a)\,Re)$<br>$C_3 = [1-(1-x)^4]$ | I |
| $C_m = C_{xl}(s/a)^{0.1}/(Re^{0.5})$<br>$C_{xl} = 0.1528 + 6.74x - 8.72x^2 + 3.75x^3$ | II |
| $C_m = 0.0311\, C_4 (s/a)^{-0.25}/(Re^{0.25})$<br>$C_4 = [1-(1-x)^{19/4}]$ | III |
| $C_m = C_{x3}(s/a)^{0.1}/(Re^{0.2})$<br>$C_{x3} = 0.006 + 0.168x - 0.235x^2 + .107x^3$ | IV |

**Pressure characteristic of Hydrodynamic disc seal**

The pressure characteristic is based on the assumption that the radial pressure gradient is equal to that experienced for a fluid mass rotating about its own axis with an angular velocity equal to kω.

The governing equation is therefore

$$dP/dr = \rho(k\omega^2)r \qquad (1)$$

The pressure difference from r=R to r= a is given as:

$$\Delta p = \rho(k\omega^2)(a^2-R^2)/2 \qquad (2)$$

**Flow characteristics**

The quantity of fluid which is pumped radially by the disc as a result of centrifugal forces is

$$Q = 2\pi a \int_0^{\delta} u\,dz \qquad (3)$$

For calculating this integral, first a velocity profile should be assumed and then the integral should be calculated.

Working domain in our problem usually is within fourth regime, so only the equation of this regime has been presented.

$$Q/\omega/^{3} = 2\pi\pi(\gamma/(\nu/\beta^{0.2})(\alpha\alpha/^{0.2})(1-k)/k^{0.2} \qquad (4)$$

**Designing the test rig**

For designing the test rig, these stages have been done.

1- Preparing the test standards and procedures
2- Drawing the sketch on the basis of wanted properties and arranging the elements of the test rig
3- Determining the required equipments for the test rig
4- Obtaining HDS dimension that should be tested.
5- Designing and calculating of elements that include:
   a) test chamber and shafts
   b) bearings and seals
   c) other elements and connections
6- Draw the final drawings and assembling

Test rig and its element have been designed on the basis of mechanical engineering knowledge. In order to complete the test results, the main suggestion is a numerical analysis of HDS (Hydrodynamic Disc Seal).

**Test standards preparing**

First step in designing each apparatus is the determination of that apparatus design standards. In this project, we could not find any standard or procedure that focus directly on performing HDS test. However standards that discuss generally about hydraulic parts and their tests were used. In addition, HDS works as a centrifugal pump therefore pump's test standards were used to determine conditions and to do measurement tasks.

Most important standards that have been gathered are:

- ISO5198: Centrifugal, mixed flow and axial pumps-Code for hydraulic performance tests precision class
- MIL-H-25475 Hydraulic Systems, Missile, Design, Installation Tests, and Data Requirements, General Requirements For
- MIL-P-27409 Propellant Feed System, Rocket Propulsion, General Specification For
- MIL-R-5149 Rocket Engine, Liquid Propellant, General Specification For

MIL-C-27410 Components, Rocket Propulsion Fluid System, General Specification For

Refs [1, 4] are complete and cited documents that have been published in this subject until now. These two references were used to determine test method and procedures.

**Test procedures**

**Test time**

According to MIL-H-8775 minimum time in leakage test is two minutes and MIL-H-25475 standard, has mentioned that number of cycle required to do hydrodynamic test is two times of the operation cycle.

**Pressure**

According to MIL-H-25475, MIL-C-27410 the produced pressure should be 150 percent more than design pressure.

Primary test rig scheme is provided as below.

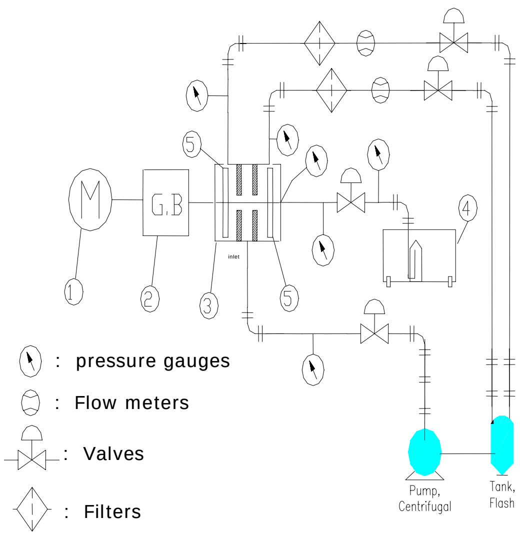


Fig (4): TEST LAYOUT

**Required Equipment**

1- centrifugal pump to produce inlet pressure
According to working domains of HDS in turbo pumps, maximum pressure and flow have been considered. Therefore the electro pump type 32/10 selected from PUMPIRAN company catalogue.

2- Electromotor to supply HDS consumption power
Consumption power of one HDS was calculated in the ref [4]
Usually, 3% of turbo pumps Consumption power, respect to overcome mechanical losses that include bearings and seals. To consider these losses, minimum required power determined. According to electromotor category, 75kw electromotor has been used. Rotational speed of selected electromotor is 3000(2950) rpm. This kind of motor is asynchrony and can increase acceleration to reach nominal speed with triangle-star method.

3- Gearbox to supply rotational speed
To obtain required rotational speed of apparatus, we have to use increasing gearbox. ***Antriebe Ag*** Company, produce increasing gearboxes. In the basis of company's site ***www.voithturbo.de***, the gearbox with this specification was selected
i=5, max power=120 kW, type ***B3-ER25***

For connecting electromotor shaft's to gearbox, special coupling has needed that can work in high power so this type of coupling was used. In order to connect gearbox shaft and test chamber, another special coupling is needed that can work in high speed. In this apparatus, TB Woods's products were used. 1½ HSMG model was used that is available for working at 20000 rpm.

**Measurement instruments and test orbit:**

According to ISO5198, Test orbit, measurement instrument and working fluid condition has been selected.

**Test apparatus elements design**

a) chamber design
Minimum thickness of chamber's wall has gotten from imported stresses to this chamber.
Maximum pressure is predicted with this equation:

$$P_{max} - P_{inlet} = \rho\omega^2 r^2 k_v^2 (1 - X^2)/2 \quad (5)$$

According to MIL-C-27410 standard, more than 150 percent of working pressure has considered to suggest the chamber pressure in tank design.
To determine minimum length that required in the chamber, first the used parts in the chamber should be identified. Therefore the scheme of chamber is presented below. (FIG5)

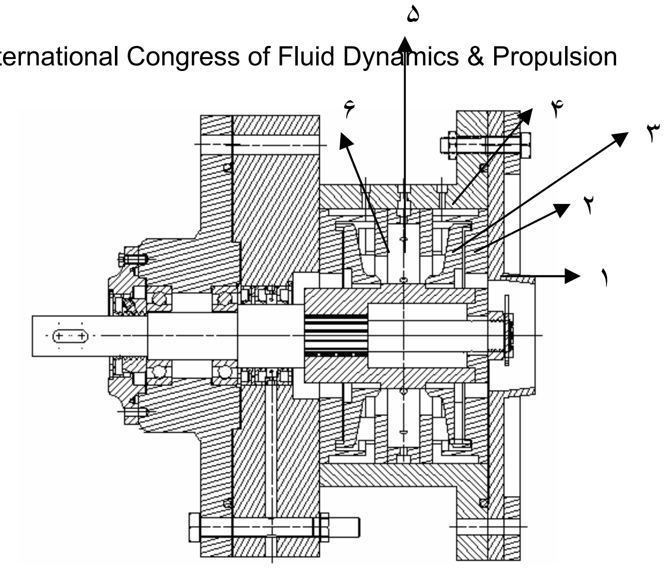


FIG (5) test chamber
1-glasses cover 2- regulating bush 3- HDS (hydrodynamic disc seal) 4- chamber body 5- assembling ring 6- input collector

In the test rig, two discs were used as follow reasons:

1- Hydraulic symmetry: if one disc was used, due to high speed rotation, sealing leakage flow from other side is too difficult.
2- Neutralization of axial forces in bearings: setting one discs in manner that smooth side of it to be in front of smooth side of the other disc.
3- It's a gain in rig that takes twice data from one test.

**How does test rig work?**

Fluid enters to chamber from this section (part number6) and because of hydraulic symmetry, half of inlet flow guides to smooth side of HDS. When HDS is rotating, fluid takes energy and main segment of flow exit from the upper side of HDS with high pressure.
Some amount of fluid leak to van side and vans don't permit the fluid to pass, although a little fluid reach to the root of HDS but immediately convert to vapor due to rotational speed of shaft that cause the reduction of fluid pressure to the vapor pressure of fluid. However a boundary layer is generated to separate between two phases of fluid (cavitations have happen)
One of the advantages of HDS is ability to convert liquid leakage to vapor leakage and as you know vapor leakage needs statically sealing less than liquid leakage.

For inlet flow to prevent direct contacting to high speed shaft a ring is used to enter fluid into chamber from different direction with uniform velocity. This ring has an outer hole that fluid enters it and then flow from perimeter inner holes enters to space of test chamber.
Availability for testing all range of HDS, is prepared with designing part number2, this part provides different dimension and clearance (axial and radial) for investigation in test rig.
As for showing in FIG (5), right side of chamber case (4), a glasses cover (1) has set that this cover has been connected to test chamber with plastic ring &nut & screw. Glasses cover

is used to see cavitations phenomena at van side during test. Test chamber (4) has been connected with welding to oil seal chamber (7) from left side. Then via nut & screw has been connected to ball-bearing chamber. Cover (9) has been used to regulate and lubricate.

**Shaft design**

Shaft outer diameter has been determined from other element arrangement. For testing all kind of HDS, shaft with different dimension should be used. Therefore shaft has been divided in two sections. At fix section, ball-bearing and oil sealing has been installed. Chamber is designed symmetrically so axial forces are neglect able.

Rotary parts (shaft and discs) should be balanced. Unbalanced masses have been measured with balance apparatus and its value shall be less than permissible unbalances that acquire form IS01940 standard.

Due to high rotational speed, special bearing must be used. Therefore ball-bearings with angular contact high speed from SKF catalogue (precision class) have been selected. O-rings and oil sealing are used to seal leakages.

**Test stand designing**

Figure (6) has showed how chamber is connected to test stand. Stand has some drawer holes to move horizontal direction for regulating.

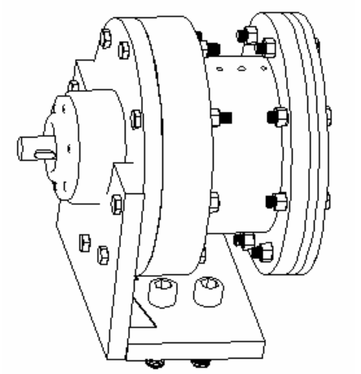

Fig (6): test chamber and connection to stand

Figure (7) has showed elements setting on the foundation. Rig Basis has connected to cement foundation with eight bolts.

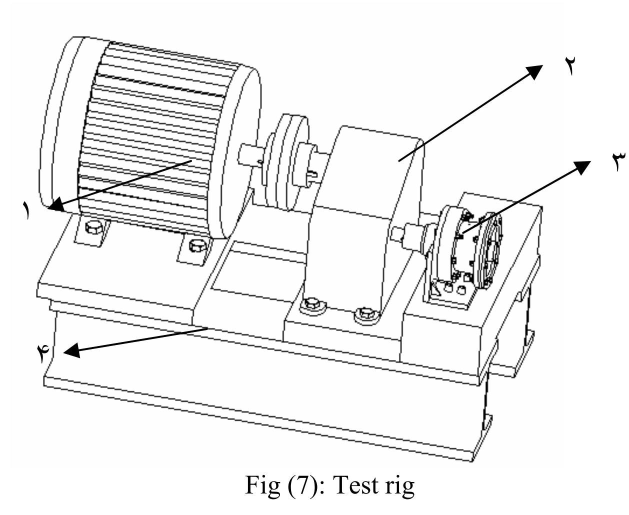


Fig (7): Test rig

1- Electromotor 2- gearbox 3- test chamber

4- stand foundation

For axial regulating and coupling electromotor-gearbox, drawer holes have designed for gearbox bolts.

**Conclusion**

As mentioned in this paper, sealing devices are almost the most important problems in high speed turbo pumps. Turbo pump test has much cost considering so subsystem tests such as sealing elements test is the best way to reduce costs. HDS is a sealing device that has extra missions such as cooling bearing and increasing pump volumetric efficiency. In this paper designing results of a HDS test rig has described.

This project has been done during specific time with manufacturing problem considering. And these steps during this project have been done:

1- Literature survey and collecting references & sources
2- HDS phenomena investigation

In this stage final equation about HDS has gathered. Although flow analysis of HDS can be investigate in different paper.

3- Preparing test standards and procedures
4- Designing Test rig

Test rig and its elements have been designed on the basis of mechanical engineering knowledge. With this designed test rig, all of the HDS can be done (Hydrodynamic Disc Seal).

**Acknowledgment**

We would like to thank B.H.R (British hydrodynamic research group) and Professor Martin Thew because of introducing some useful references.

**References:**

[1] Thew M.T. and Sanders M.G. “The Hydrodynamic disc seal” Proc.Third international conference on fluid sealing, Cambridge, England Paper No.H5. pp.H5-97 to H5-124. (April, 1967)

[2] Ketola H.N, McGrew J.M. “Theory of the partially wetted disc” Third international conference on fluid sealing. Cambridge, England. PaperNo.H5 pp.H4-69 to H4-94 (April, 1967)

[3] Гидродинамические радиальные уплотнения высокооборотных валов. Краев М.В., Овсяников Б.В.,Шапиро А.С. Изд."Машиностроение", 1976,

[4] Oberg, Erik, Machinery’s Handbook, 25th edition, 1996

[5] Конструкция и проектирование ЖРД. Под ред. Г.Г.Гахуна, . Изд."Машиностроение", 1989