CENTRIFUGAL PUMP MECHANICAL SEAL AND BEARING RELIABILITY OPTIMIZATION

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Abstract: Centrifugal pumps are used in a wide range of field and industrial applications and as significant rotating equipment, incurred high real life costs. The earlier researches illustrate that the main cost is borne by the seals and bearings as critical components of the pump. Most of the pump maintenance work is initiated by the failure of a mechanical seal or bearing as well. Reliability allocation is developed for the early design stage of a system to apportion the system reliability requirement to its individual subsystems. This article examines possible approaches to allocate the reliability values to the components of the mechanical seals and bearings such that the total cost is minimized. The cost of increasing reliability of these components is considered as an exponential function that contains four parameters of component reliability, feasibility factor, maximum achievable reliability and minimum reliability, which is estimated by Monte Carlo simulation. The Genetic Algorithm (GA) optimization is applied to the reliability allocation topic for a typical mechanical seal and bearing components. Optimization process yield optimum values of the components reliabilities, while considering the cost function as an objective in the GA method.

Keywords: Centrifugal pump, Mechanical seal, Bearing, Reliability allocation, Genetic algorithm, Monte Carlo

1. INTRODUCTION

Before a pump can be selected or a prototype designed, the application must be clearly defined. Whether a simple recirculation line or a complex pipeline is needed, the common requirement of all applications is to move liquid from one point to another. As pump requirements must match system characteristics, analysis of the overall system is necessary to establish pump conditions. This is the responsibility of the user and includes review of system configuration, changes in elevation, pressure supply to the pump, and pressure required at the terminal. Relevant information from this analysis is passed on to the pump manufacturer in the form of a pump data sheet and specification.

Centrifugal pumps are extensively used in different industries and in some instances number of utilized pumps could easily count to hundreds of pumps. A pump is usually classified into two general classes of centrifugal and positive displacement. The centrifugal pump has two main parts: a rotating element which includes an impeller and a shaft, and stationary elements made up of a casing, the mechanical seal, and the bearings. With centrifugal pumps, the energy is added continuously by increasing the fluid velocity with a rotating impeller while reducing the flow area.

Centrifugal pumps are the most common type of kinetic pumps and these pumps are used in a wide range of field and industrial with moderate to high flow and low head applications. Mechanical seals are used in centrifugal pumps to provide a leak proof seal between the component parts. There are many different designs for mechanical seals to meet specific applications. Mechanical seal is compromised of the primary and mating rings. When in contact they form the dynamic sealing surfaces that are perpendicular to the shaft. The primary ring is flexibly mounted in the seal head assembly, which usually rotates with the shaft. The mating ring with a static seal, forms another assembly that is usually fixed to the pump gland plate. Each of the sealing planes on the primary and mating rings is lapped flat to eliminate any visible leakage. The basic components of mechanical seal of a centrifugal pump are shown in the Fig. 1 [1].

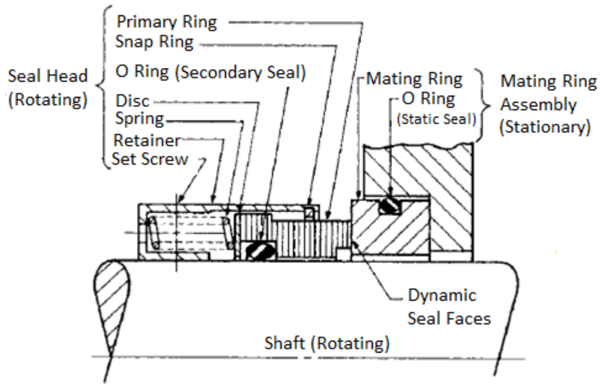

Figure 1: Schematic of Pump Mechanical Seal [1]

Bearings are manufactured to take pure radial loads, pure thrust loads, or a combination of the these two kinds of loads. The nomenclature of a ball bearing is illustrated in Fig. 2, which also shows the four essential parts of a bearing. These are outer ring, inner ring, balls or rolling elements, and separator.

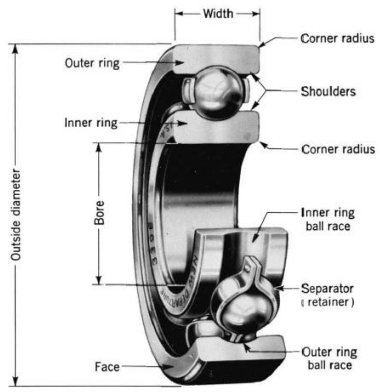

Figure 2: Schematic of Pump Bearing [2]

More than eighty percent of root causes of rotating equipment outages are related to failures of mechanical seals and bearings. Recently, there is great attention on mechanical seal and bearing failures and reliability. For instance, failures of mechanical seals are evaluated in [3-[4], failure modes are analyzed in [5] and improving reliability of seals is discussed in [6-[9]. In addition for increase the reliability of the pumps, researches have been conducted on bearings [10-[13]. A designer needs to achieve the target reliability while minimizing the total cost. Intuitively, some of the lowest reliability components may need special attention to raise the overall reliability level. Such an optimization problem may arise while designing complex system. The cost is formulated as a function of reliability and it has an exponential behavior. It is assumed that the cost function satisfy three conditions. Cost function is a positive definite function, non-decreasing and increases at a higher rate for higher values of reliability. This mathematical formulation depends on certain parameters that they are calculated in this article.

Here, the reliability of the seal and bearing are allocated to the components with optimum value to achieve the minimum cost of increasing their reliability. The minimum required reliability for each component of a seal and a bearing are approximated in order to achieve a system reliability goal with minimum cost and this minimum required component reliability will be achieved via fault avoidance [14]. Monte Carlo method is used for the evaluation of minimum reliability. Feasibility parameter is evaluated for application in the cost function. The maximum achievable reliability of each component is considered 99.99%. The problem of reliability allocation and optimization has been widely treated by many authors. A number of studies have examined these problems for last several decades [15].

2. SCOPE AND OBJECTIVE

This research is aimed to determine optimum reliability value for mechanical seal and bearing components subject to minimization of the specific cost function. Total cost is sum of each component cost. Cost is a function of the components minimum reliability and Monte Carlo method is used for estimating the minimum reliability value. Feasibility parameter is evaluated according to the different indexes like state of the art, complexity, environment and operating time.
Here, GA model is developed based on a binary coding that can easily deal with variables for finding minimum cost of mechanical seal and bearing components of a centrifugal pump. Components reliabilities are used as random variables in the optimization model based on GA. Optimized parameters are resulted as output of the GA.
Mechanical seal and bearing failure modes of a centrifugal pump are defined in section 3. Monte Carlo method which is used in the calculation of minimum reliability of components is described in section 4. The details of the GA programming methodology are given in section 5. Defining the cost function that is used as an objective function in the GA method and determining of the unknown parameters of this function are explained in section 6. The results of the program are presented in section 7 and these results are discussed in section 8. Concluding remarks are provided in section 9.

3. MECHANICAL SEAL AND BEARING FAILURE MODES

Failure mode and effect analysis (FMEA) is a powerful technique for reliability analysis. This method is inductive in nature. The FMEA analysis describes inherent causes of events that lead to a system failure, determines their consequences, and devises methods to minimize their occurrence or recurrence. Here, the information about the critical failure modes and the related failure causes with effects of the pump mechanical seal and bearing are in Table 1 and 2. When mechanical seals are properly applied, there should be no static leakage and, under normal conditions, the amount of dynamic leakage should range from none to just a few drops per minute. If excessive leakage occurs, the cause must be identified and corrected. Causes for seal leakage with possible corrections are listed in Table 1.

Table 1: The FMEA of Mechanical Seal [16-20]

No.	Potential Failure Mode	Potential Cause(s)/Mechanisms of Failure	Potential Effect(s) of Failure
1	Leakage for secondary seals	Installation problems	Seal drips steadily
		Overaged Oring	
		Chemical attack	
		Poor maintenance	
2	Excessive clearance around the seal	Weakness in distortion resistance	Stuffing box leaks abnormally
		Excessive preloads on seal faces	
		Excessive vibration	
		Excessive flush flow	
3	Leakage between rotary and stationary ring	Vibration	Seal life is short
		Poor maintenance	Seal leaks
4	Faces not flat	Foreign particles between seal faces	Seal faces blistered and distorted
		Problems of gland gasket for proper compression	
		Improper material	Seal drips steadily
		Chemical attack	
		Improper cooling of flush lines	Seal life is short
		Incorrect installation	
5	Seal fluid vaporizing	Bypass flush line	Seal spits and sputters
		Problems in gland plate orifices	Seal life is short
6	Inadequate amount of liquid to lubricate seal faces	Bypass flush line	Seal squeals during operation
		Problems in gland plate orifices	Seal life is short

In order for bearing to operate properly, the equipment must be in good condition. The main failures of a bearing are related to mounting, vibration, dirt and improper lubrication. Table 2 lists common troubles that affect the bearing life.

Table 2: The FMEA of Bearing [19-22]

No.	Potential Failure Mode	Potential Cause(s)/Mechanisms of Failure	Potential Effect(s) of Failure
1	Improper mounting	Not observing the basic concepts	Bearings do not give good service life
		Improper workmanship during installation of bearings	Pump operates with noise or vibrations, or both
			Excessive radial or axial load
2	Vibration	Cavitation	Balls and rollers to jam into the
		Bent shafts	
		Unbalanced rotary assemblies	
		Shock thrust loads	The surfaces of the balls and rollers begin breaking away
		Slapping v-belts	
		Improper foundation	
3	Dirt and Abrasion	Careless handling during storage and assembly	Contamination between the balls and races can start a round of false brinelling
			Pump operates with noise or vibrations, or both
			Mechanical seal and stuffing box fails prematurely
4	Inadequate Lubrication	Wrong type of lubricant	Too much friction
			High heat
			Metal-to-metal contact between rolling and stationary elements
			Pump draws higher amps than specified
5	Excessive Lubrication	Too much lubrication	Forming the foam and froth mixed with air
			Overheating
			Pump draws higher amps than specified

4. MONTE CARLO SIMULATION AND ERROR BOUNDS

Monte Carlo Simulation (MCS) is a method that presents the following characteristics: it is applied to many practical problems allowing the direct consideration of any type of probability distribution for the random variables; it is able to compute probability of failure with desired precision; and it is easy to implement.
In reliability analysis the Monte Carlo simulation is used when the analytical solution is not attainable and the failure domain can neither be expressed nor approximated by an analytical form. A reliability problem is formulated using a failure function, $g(X_1,X_2,X_3,...X_n)$, where $X_1,X_2,X_3,...X_n$ are random variables. Violation of the limit state is defined by the condition $g(X_1,X_2,X_3,...X_n)\leq 0$ and the probability of failure, $\hat{p}_f$ is expressed by the following expression:

$$\hat{p}_f = \frac{\sum_{i=1}^{N_T} I(X_1,X_2,X_3,...X_n)}{N_T} \quad (1)$$

Where $I(X_1,X_2,X_3,...X_n)$ is a function defined as:

$$I(X_1, X_2, X_3, \ldots X_n) = \begin{cases} 1 & if \quad g(X_1, X_2, X_3, \ldots X_n) \le 0 \\ 0 & if \quad g(X_1, X_2, X_3, \ldots X_n) > 0 \end{cases} \tag{2}$$

Here, NT independent sets of values are obtained based on the probability distribution for each random variable and the failure function is computed for each sample. Using direct simulation Monte Carlo, an estimate of the reliability of component is obtained by:

$$\hat{R} = \frac{N_S}{N_T} \tag{3}$$

where, N_S is total number of successful trials in the simulation [23].
Monte Carlo estimates have associated error bounds. The Monte Carlo trials are discrete events and independent of each other. Consequently, their outcome follows the binomial distribution [24]; the beta inverse cumulative distribution function is used to determine the lower and upper confidence limits on the reliability predicted by the Monte Carlo simulation method at desired confidence levels. Here, the desired confidence level is considered 95%.

5. GENETIC ALGORITHM

A genetic algorithm generates the initial population of solutions. This population evolves over successive generations based on the survival of fitness. The operations such as reproduction, cross over and mutation are performed on the populations and the fitness of each individual is evaluated. Based on the new fitness of each individual, the population of next generation is produced probabilistically and the individuals with poor fitness will disappear, and the individuals with high fitness will survive. The genetic algorithm can search huge space rapidly. The GA starts with a group of chromosomes known as the population and a matrix of uniform random numbers between zero and one is generated.
In evaluation process, only the best candidate solutions are selected to continue, while the rest are deleted. These elite individuals are passed to the next population.
Mating is the creation of offspring from the parents selected in the pairing process.
Random mutations alter a certain percentage of the bits in the list of chromosomes and change the characteristics of a gene. Mutation is the second way a GA explores a cost surface. A single point mutation changes a 1 to a 0, and vice versa [25].
The number of generations that evolve depends on a set number of iterations is exceeded. The best string seen up to the last generation provides the solution to the problem. Here, after 1000 generations the algorithm is stopped.

6. COST FUNCTION

There is always a cost associated with changing a design due to change of vendors, use of higher-quality materials, retooling costs, administrative fees, etc. The cost as a function of the reliability for each component is quantified before attempting to improve the reliability. The preferred approach would be to formulate the cost function from actual cost data. In many cases however, this data is not available and is hard to obtain. For this reason, a general behavior model of the cost versus the component's reliability was developed for performing reliability optimization. The proposed cost function is [14]:

$$C = \sum_{i=1}^{n} c_i(R_i) = \sum_{i=1}^{n} \exp\left[(1-f_i)\frac{R_i - R_{i,\min}}{R_{i,\max} - R_i}\right] \tag{4}$$

where, the constraint is $R_s \ge R_G$ and each variable range is $R_{i,\min} \le R_i \le R_{i,\max}, i = 1, 2, \ldots, n$ and this function is for a system consisting of n components. $R_{i,min}$ is minimum reliability of a component, $R_{i,max}$ is maximum reliability of a component, f is the feasibility (or cost index) of improving a

component's reliability relative to the other components in the system, R_G is goal reliability and R_s is system reliability.
The cost increases as the allocated reliability departs from the minimum or current value of reliability and it increases as the allocated reliability approaches the maximum achievable reliability. The cost is a function of the range of improvement, which is the difference between the component's initial reliability and the corresponding maximum achievable reliability. It is easier to increase the reliability of a component from a lower initial value.

6.1. FEASIBILITY

The feasibility parameter is a constant, which represents the difficulty in increasing component reliability relative to the rest of the components in the system. Depending on the design complexity, technological limitations, etc., certain components can be very hard to improve, relative to other components in the system [13]. Weighting factors for allocating reliability have been proposed by [26], are used to quantify feasibility. This parameter is given by

$$f_i = \frac{I_i}{\sum_{j=1}^{n} I_j} \quad (5)$$

For any component:

$$I = A(C + E + T) \quad (6)$$

Where A is state of the art index, C is complexity index, E is environment index, and T is operating time index. The state of the art index is given by:

$$A = K^{\upsilon} \;\; ; \;\; \upsilon = a^{-T_w} \quad (7)$$

T_w is number of years during which work has been done on the component, a=0.9842 for bearing and mechanical systems and K factor is defined as below:

$$K_i = \lambda_i K_{bi} \Big/ \sum_{j=1}^{n} \lambda_j K_{bj} \quad (8)$$

$$K_{bi} = 10 n_{bi} / n_{bc} \quad (9)$$

Where λ_i is failure rate for component i, n_{bi} is number of parts in component i and n_{bc} is number of parts in the most complex component.
The complexity index is given by:

$$C = 1 - e^{-K_b + 0.6K_p} \quad (10)$$

K_b is described in the previous paragraph and K_p is defined as below:

$$K_{pi} = 10 n_{pi} / n_{pc} \quad (11)$$

where n_{pi} is number of redundant parts in component i and n_{pc} is number of redundant parts in the most complex component.
The environment index is given by:

$$E = 1 - \frac{1}{f'} \quad (12)$$

where f' is unit stress. The stress level at which complete failure is expected, a value of 100 is assigned and at which no failure is expected, a value of 0 is assigned.
The operating time index is given by:

$$T = \frac{T_m}{T_u} \quad (13)$$

where T_m is total mission time of the item and T_u is operating time of the component.

The assessment of this parameter is summarized in Tables 3 and 4 for ten years. Failure rates of the components are estimated in accordance with [20] and are in fails/ million hours.

Table 3: Data for feasibility evaluation for mechanical seal

No.	Components	n_b	K_{bi}	λ_i	f'	A	C	E	I	F
1	Disc	1	1.666	0.0567	35	2.86E-02	0.811	0.971	5.26E-02	3.63E-02
2	Flush lines	2	3.333	0.0486	30	5.38E-02	0.964	0.966	1.09E-01	7.49E-02
3	Gland plate	6	10.0	0.0567	35	2.34E-01	0.999	0.971	5.22E-01	3.60E-01
4	O-ring (secondary seal)	1	1.666	0.1135	70	6.45E-02	0.811	0.986	1.21E-01	8.34E-02
5	O-ring (static seal)	1	1.666	0.0973	60	5.38E-02	0.811	0.983	1.00E-01	6.92E-02
6	Primary & Mating ring	2	3.333	0.0973	60	1.21E-01	0.964	0.983	2.53E-01	1.74E-01
7	Retainer	1	1.666	0.0243	15	1.06E-02	0.811	0.933	1.93E-02	1.33E-02
8	Set screw	3	5.0	0.0162	10	2.39E-02	0.993	0.9	4.82E-02	3.32E-02
9	Snap ring	1	1.666	0.073	45	3.84E-02	0.811	0.978	7.10E-02	4.90E-02
10	Spring	2	3.333	0.065	40	7.54E-02	0.964	0.975	1.54E-01	1.06E-01

Table 4: Data for feasibility evaluation for bearing

No.	Components	n_b	K_{bi}	λ_i	f'	A	C	E	I	F
1	Balls	8	10	0.00375	60	0.62	0.999	0.983	1.854	0.7457
2	Rings	2	2.5	0.00375	73.3	0.12	0.864	0.986	0.349	0.1402
3	Lubricant	1	1.25	0.00375	40	0.05	0.632	0.975	0.141	0.0568
4	Cage	1	1.25	0.00375	71.6	0.05	0.632	0.986	0.142	0.0571

6.2. MAXIMUM ACHIEVABLE RELIABILITY

In reliability allocation, a limiting reliability value is defined. The cost function near this value is high and it is influenced by technological and financial constraints. The maximum achievable reliability acts as a scale parameter for the cost function. By decreasing $R_{i,max}$, the cost function is compressed between $R_{i,min}$ and $R_{i,max}$. In this paper, the maximum achievable reliability is considered 99.99% for each component of a mechanical seal and a bearing.

6.3. MINIMUM RELIABILITY OF COMPONENTS

The cost is a function of minimum reliability of each component. To estimate this parameter of cost function, Monte Carlo method is used. Here, minimum reliability of 10 main components of a centrifugal pump mechanical seal and 4 components of a bearing is predicted using this method.

In a mechanical seal, the spring load is applied on primary ring to keep the seal faces in contact and this load is distributed uniformly by a metal disc. The reliability of the disc, flush line and gland plate are predicted based on state, cooling capability and safety factor, respectively. Design parameters of dynamic O-ring seal are considered pressure, leakage, seal size, hardness, surface finish, temperature and PV coefficient. Design parameters of static O-rings are like the dynamic O-rings. In static seals, surface finish has a different value and PV coefficient is not applicable for this kind of O-rings.

The basic components of a mechanical seal are the primary and mating rings. Together they form the dynamic sealing surfaces, which are perpendicular to the shaft. The primary ring is part of the seal head assembly, while the mating ring and static seal form a second assembly, making a complete installation for a pump [16]. PV coefficient and heat transfer in a mechanical seal are considered as design factors for this assembly. A metal retainer locked to the shaft and provides a positive drive through the shaft and to the primary ring. The reliability of retainer is predicted based on safety factor of applied stress and its strength. The function of set screws is to restrict or control motion. The reliability of the set screw is predicted based on its strength. The snap ring retains the assembly on the

shaft and the reliability of the snap ring is predicted based on groove deformation. The reliability of the spring is predicted based on its strength.
In a bearing, the balls are inserted into the grooves by moving the inner ring to an eccentric position. The balls are separated after loading, and the separator is then inserted. The use of a filling notch in the inner and outer rings enables a greater number of balls to be inserted, thus increasing the load capacity. The thrust capacity is decreased, however, because of the bumping of the balls against the edge of the notch when thrust loads are present. The angular-contact bearing provides a greater thrust capacity. The minimum reliability of these components is predicted based on strength and applied stress. The calculations results are summarized in the Table 5 and 6.

Table 5: Minimum Reliability Evaluation for Mechanical Seal

Components	R_{min}	Lower limit	Upper limit	Iterations
Disc	98.25%	98.22%	98.27%	1,000,000
Flush line	92.6%	92.54%	98.64%	1,000,000
Gland plate	95.95%	95.91%	95.99%	1,000,000
Dynamic seal	90.1%	89.91%	90.28%	100,000
Static seal	91.85%	91.67%	92.18%	100,000
Retainer	97.98%	97.95%	98%	1,000,000
Setscrew	93.67%	93.63%	93.72%	1,000,000
Snap ring	96.7%	96.66%	96.73%	1,000,000
Spring	96.34%	96.3%	96.37%	1,000,000

Table 6: Minimum Reliability Evaluation for Bearing

Components	R_{min}	Lower limit	Upper limit	Iterations
Balls	95%	94.87%	95.96%	1,000,000
Rings	90%	89.93%	90.05%	1,000,000
Lubricant	97.52%	97.49%	97.55%	1,000,000
Cage	95.86%	95.83%	95.9%	1,000,000

6.4. GOAL RELIABILITY

Cost function of mechanical seal satisfies goal reliability as a constraint. In this paper, goal reliability is determined according to [22] for 10 years operation of the pump.

7. RESULTS

Reliability allocation optimization calculation of the mechanical seal and bearing of a centrifugal pump are shown in Figures 3 and 4:

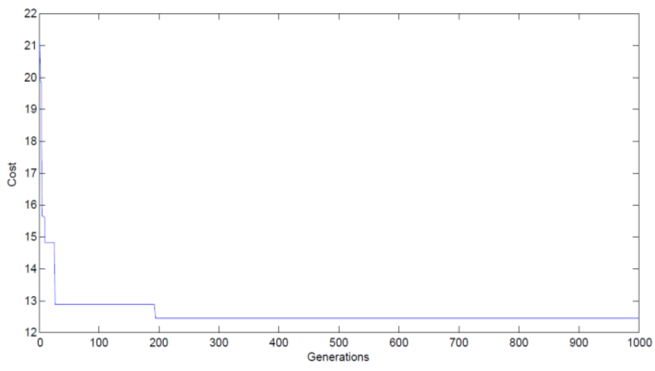

Figure 3: Convergence procedure for mechanical seal

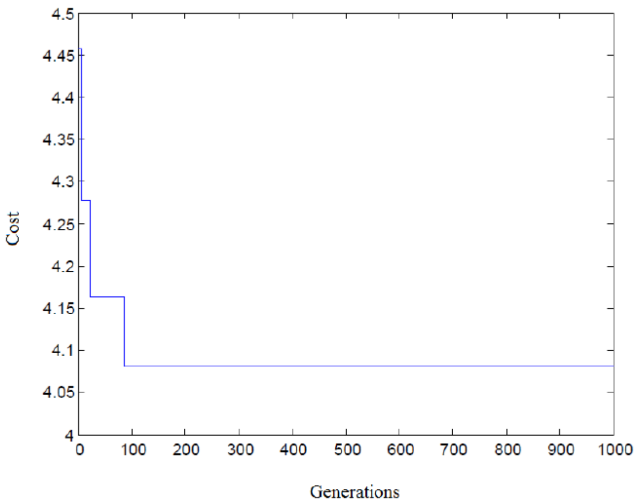

Figure 4: Convergence procedure for mechanical seal

Outputs for the reliability allocation of a mechanical seal are calculated as: R_{disc} = 98.81%, R_{flush_lines} = 94.4%, R_{gland_plate} = 96.25%, $R_{dynamic\_seal}$ = 90.4%, R_{static_seal} = 93.13%, $R_{primary\_mating}$ = 94.95%, $R_{retainer}$ = 98.21%, $R_{setscrew}$ = 93.71%, R_{snap_ring} = 97.64%, R_{spring} = 97.46%.
Outputs for the reliability allocation of a bearing are calculated as: R_{balls} = 95.47%, R_{rings} = 90.06%, $R_{separator}$ = 95.98%, $R_{lubricant}$ = 97.57%.

8. ANALYSIS OF RESULTS

In accordance with the previous results, the minimum cost of mechanical and bearing are calculated 12.45 and 4.08, respectively. The ranking of the optimized reliabilities shows that for mechanical seal, the minimum increase of reliability is related to the set screw and the maximum increase of reliability is related to the flush line. In addition, the ranking of the optimized reliabilities shows that for bearing, the minimum increase of reliability is related to the lubricant and the maximum increase of reliability is related to the balls. These values can be used at least for the initial designing of the mechanical seal and bearing components. Optimizing design with respect to the reliability is a step to design a reliable centrifugal pump.

9. CONCLUDING REMARKS

In this article the mechanical seal of and bearing of a centrifugal pump were evaluated for reliability optimization problem through reliability allocation at the component level. A general cost function with estimated parameters is used as an objective function for the optimization with GA method. These parameters can be altered and different allocation scenarios are investigated. GA is utilized to solve constrained optimization problems effectively. The analyzed results show that the genetic algorithm can be used as a useful decision-supporting tool to optimize the design of a pump. Fundamental techniques for performing a Monte Carlo simulation have been explained. This tool can be applied to any system that compromises smaller components with a known or at least determinable failure distribution. Monte Carlo method is applied for estimation of minimum reliability of mechanical seal and bearing components. Further research can be concentrated in obtaining such functions based on actual cost data and this procedure is applicable for the other components of the pump. The results of the analysis can then be used to provide economic justification for reliability improvements to existing equipment or to purchase new equipment for the system.

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