WORLD PUMPS November 2010

Diaphragm improvements

Improving fatigue life for diaphragms

Fatigue-induced rupture of the rubber diaphragm is one of the most common causes of failure in submersible pumps. In this article, Amin Akhbarizadeh and Alireza Araghi of Iran's Pars Koral Ghomes Co demonstrate how diaphragm fatigue life can be improved via simulation and new mechanical design.

One of the most important causes of failure in submersible pumps is rubber diaphragm fatigue. The rubber diaphragm, which is located at the bottom of the motor axle, prevents water from leaving the motor cylinder. This water cools the pump and the internal wiring. When the submersible pump is turned on, significant loads are applied to the rubber diaphragm beneath the pump. As a result of these fluctuating loads, fatigue fracture and consequently failure of the diaphragm eventually takes place. After the diaphragm tears, the water in the cylinder flows out and the cooling system will not work anymore. Hence, the PVC coatings on the wiring melt and the electromotor will fail. With respect to this phenomenon, the selection of a rubber diaphragm with a long working life and good resistance to fatigue failure is important in order to increase the working life of submersible pumps.

Fatigue behaviour

Since 1850, it has been established that materials fail under fluctuating loads that are smaller than their critical fracture load; this phenomenon is called fatigue. In rubbers and plastics, fatigue is an important failure mechanism. Fatigue failure consists of the nucleation and propagation of cracks from initial defects, leading to the fracture of the material. Fatigue in materials is usually of the brittle type, without any visible warning signs before the fracture.

If a rubber part is machined, fatigue crack growth is facilitated as a result of the surface damage produced. In crystalline polymers, this process takes place because of molecular slip and movements. In moulded rubber parts, the presence of moulding residues, such as weld lines and mould gates, and particles of reinforcing additives and pigments can accelerate the crack initiation. Moreover, stress concentration areas that are due to the component's shape are one of the most important sources of crack initiation in fatigue.

There are a variety of factors that make the fatigue behaviour of rubber diaphragms very complicated. Some of these are: 1) loading factors, including stress, strain and time; and 2) viscoelastic behaviour such as loading rate.

Simulation

Using simulation software such as the well-known ABAQUS or ANSYS systems, the stress concentration areas can be identified. These areas are the weakest parts of the object; hence, fatigue fracture occurs there due to the high load concentration. Changing the material and the mechanical design are the two main methods of increasing the fatigue life of rubber diaphragms. In most industrial applications, the first approach is to improve the mechanical design to decrease the stress concentration, thereby increasing the component's working life.

In the research discussed here, the fatigue life of rubber diaphragms used in submersible pumps was studied. Two different kinds of rubber diaphragms with different mechanical designs were investigated. Stress concentration regions were identified using the ABAQUS software. New samples of the same composition were designed and manufactured to decrease the stress concentration. To determine the fatigue life of the rubber diaphragms, a fatigue testing machine was built with the ability to test the samples with size, loading and environmental conditions similar to those for the pumps.

Experiments

In these experiments, two kinds of rubber diaphragms were investigated. These diaphragms were different in shape and design. The first diaphragm (Figure 1) is used in submersible pumps

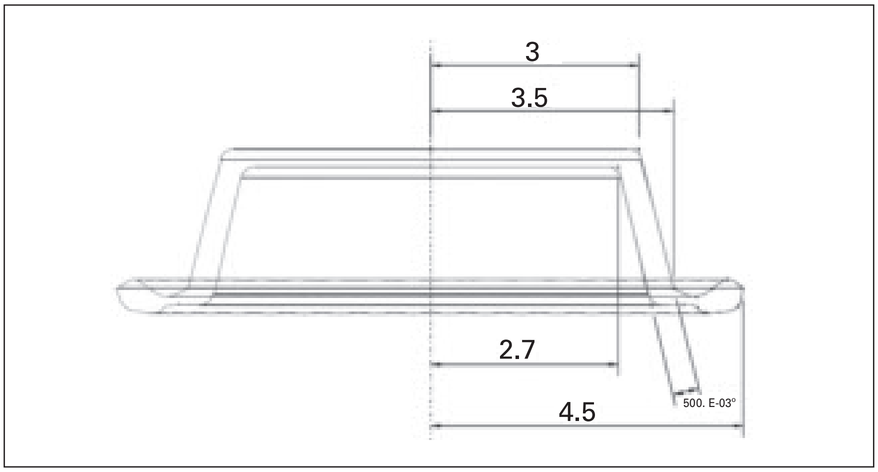

Figure 1. Scale diagram of the rubber diaphragm used in the Pumpiran pumps.

supplied by Iranian Pump Manufacturing Co (Pumpiran, Tabriz, Iran; www.pumpiran.com) and the second (Figure 2) in pumps from Rayan Electropump Industries Ltd (Tehran, Iran; www.rayan-ep.com). The diaphragm loadings for both designs were analysed by the finite element analysis method using the ABAQUS/Explicit software. To identify the areas of stress concentration, the analyses were performed using the static method.

To simulate the tensile behaviour, the three-dimensional deformable body treatment was used. To mesh the samples, the free mesh method was employed due to the complicated geometry. For the first sample (Pumpiran), tetragonal elements were chosen and for the second diaphragm (Rayan pump) they were hexagonal.

To study the fatigue life of the rubber diaphragms, a fatigue testing machine was constructed (Figure 3) capable of working in a fluid environment, changing the velocity and accurately evaluating the number of fatigue cycles before failure. The fatigue testing machine was designed in such a way that when the diaphragm failed, causing water to leak out, water-sensitive sensors instantly turned the circuit off and the number of fatigue cycles was thus accurately determined.

New designs

To decrease the stress in the areas of high stress concentration in the first rubber diaphragm, and thereby increase its fatigue life, two new mechanical designs were produced: the first a fully arched diaphragm and the second a filleted diaphragm with a fillet radius (*r*) of 0.6 cm (Figure 4). In the second of these new designs, the fillet decreases the stress concentration due to the sharp edges in the original sample. In the fully arched design, these stress concentration areas are reduced even further. The chemical composition of the diaphragms consists of equal parts (30%) by weight of natural rubber, styrene-butadiene rubber (SBR) and carbon, with the remaining 10% consisting of other components including H_2SO_4 and HNO_3. The mechanical properties of the diaphragms are given in Table 1.

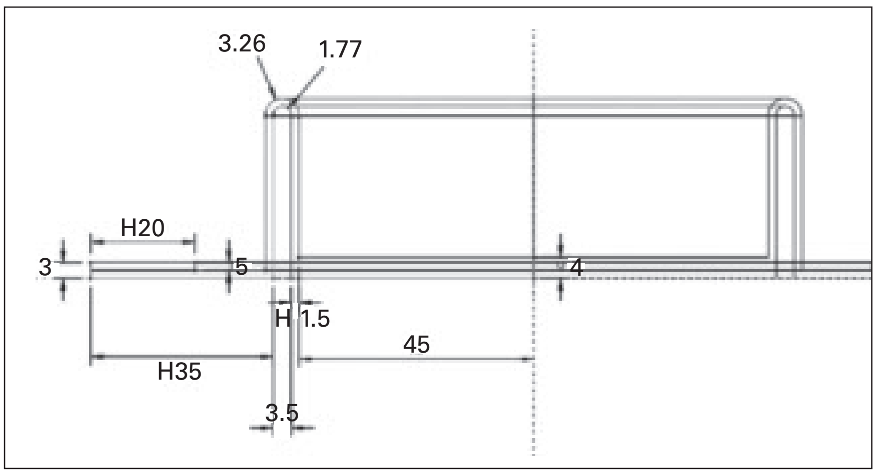

Figure 2. Scale diagram of the rubber diaphragm used in the Rayan pumps.

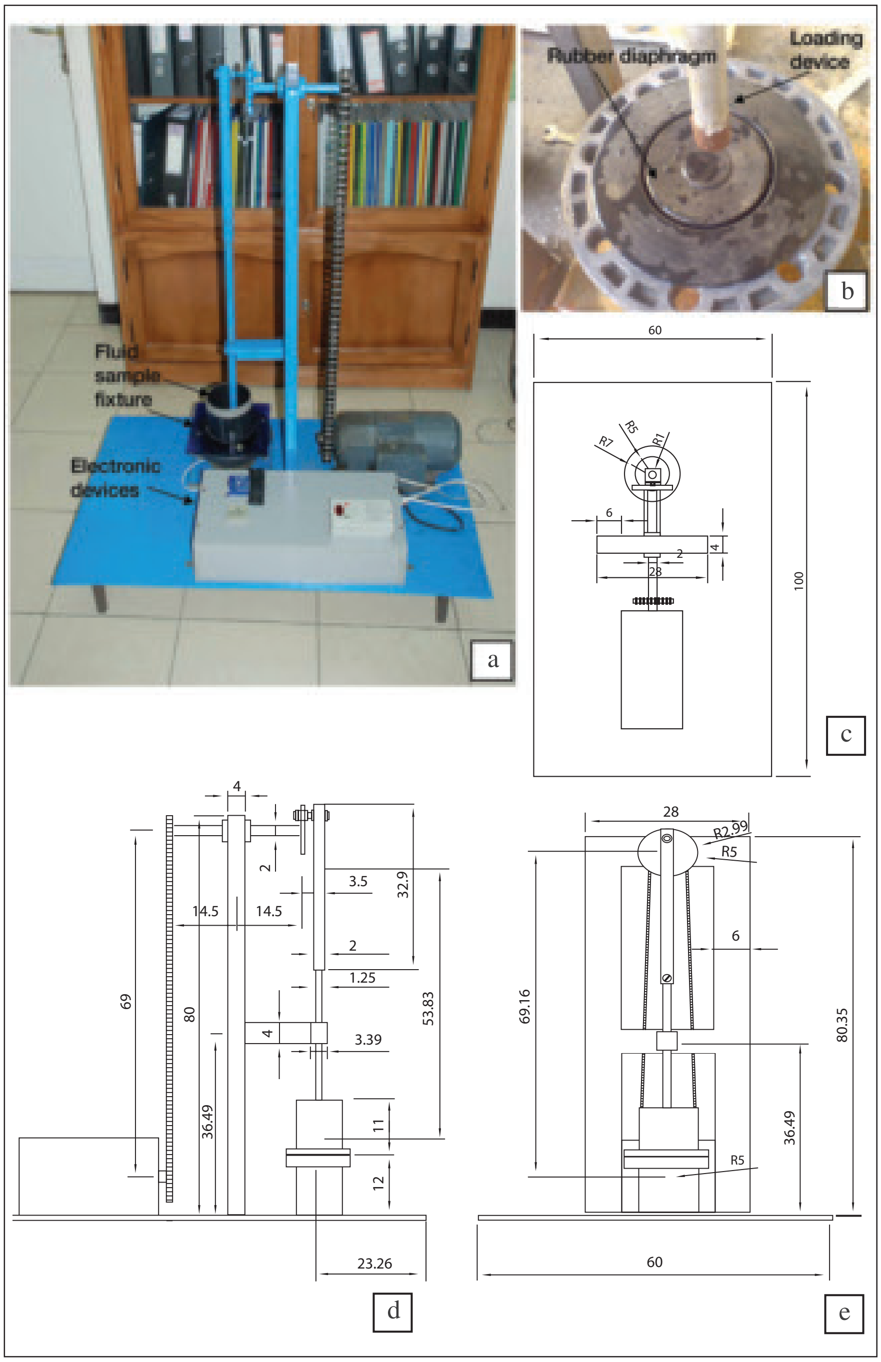

Figure 3. Fatigue testing machine: photographs of a) the full rig and b) a sample in situ, with diagrams of c) the top, d) front and e) right-side elevations.

The new mechanical design for the second diaphragm (Figure 2) involved removing the sharp corners. For this purpose, a new rubber diaphragm with filleted edges (r = 0.5 cm) was designed. The chemical composition and mechanical properties of the sample are identical to those of the first diaphragm.

Fatigue testing was conducted on the samples using the fatigue testing machine with a velocity of 120 rpm and temperature in the water environment of 25±5°C.

Stress analysis results

In the stress analysis of the original Pumpiran diaphragm (Figure 1), loads were applied as shown in Figure 5. The stresses were analysed using the Tresca criterion. In this criterion the material fails when $\sigma_1 - \sigma_3 = Y$. In this equation, Y is the yield stress of the material and σ_1 and σ_3 are, respectively, the highest and lowest principal stresses applied to the material. It should be mentioned that the principal stresses are the stresses applied to the material in the principal directions (x, y and z) without the existence of any shear stress. The stress concentration areas are shown in green in Figure 5. In this analysis, all of the fixed regions (that is, regions that do not move at all during the pump's work cycle and are fixed by other parts of the pump) are introduced as surfaces (places that do not show any movement during simulation) to the software; hence, there is no stress concentration at the bottom of the diaphragm. As shown in Figure 5, as the distance from the edges increases, the stress concentration decreases.

The stress analysis was also conducted using the von Mises criterion. According to this criterion, the materials fails when $(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 + 6(\tau^2_{12} + \tau^2_{23} + \tau^2_{13}) = 2Y^2$. In this equation, σ_1,

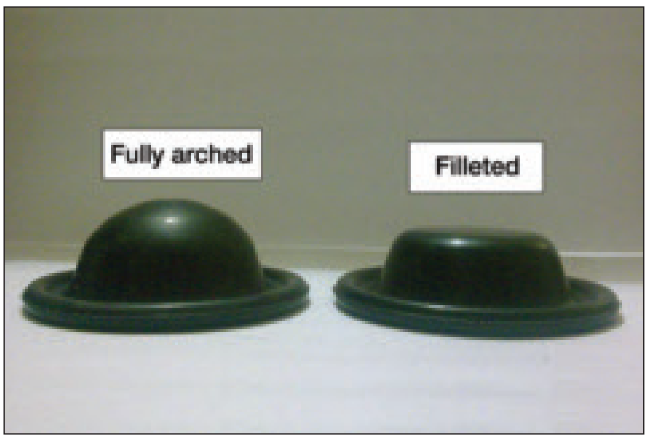

Figure 4. New rubber diaphragm designs for the Pumpiran pumps.

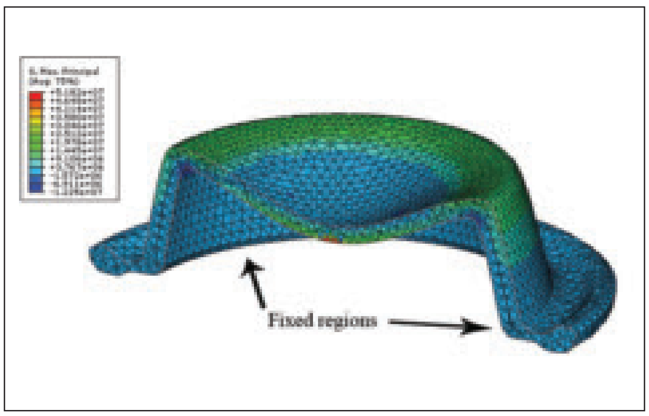

Figure 5. ABAQUS analysis of the original Pumpiran rubber diaphragm under applied stress with respect to the Tresca maximum principal stress criterion.

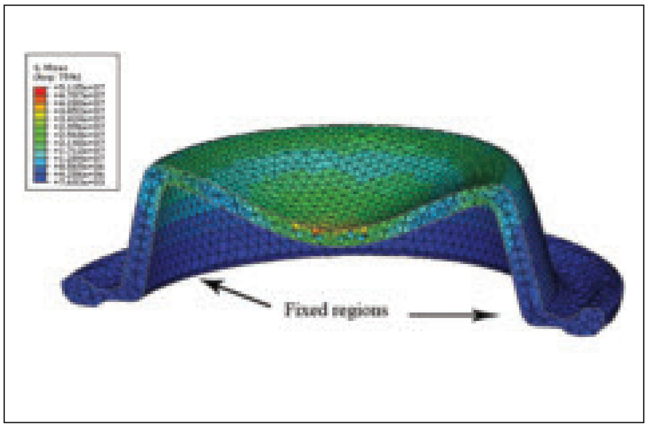

Figure 6. ABAQUS analysis of the Pumpiran rubber diaphragm under applied stress with respect to von Mises's criterion.

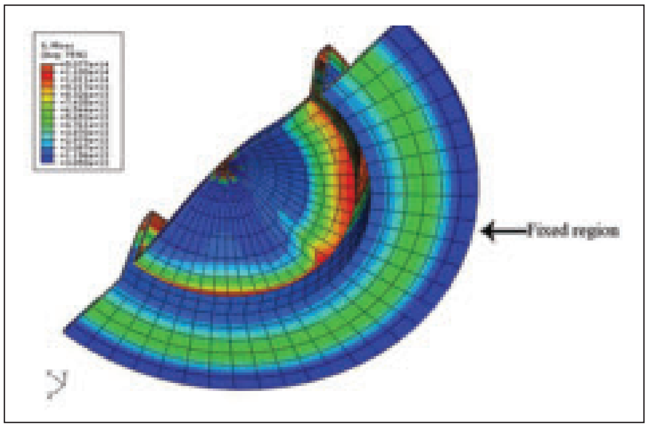

Figure 7. ABAQUS analysis of the Rayan rubber diaphragm under applied stress with respect to von Mises's criterion.

σ_2 and σ_3 are the principal normal stresses, τ_{12}, τ_{23} and τ_{13} are the principal shear stresses and Y is the yield stress of the material. As in Figure 5, this analysis again shows that the stress concentration areas are at the edges; the only difference is that the stress concentration region is closer to the deformation regions (Figure 6).

For the second rubber diaphragm (Rayan; Figure 2), the stress analysis is different from the first diaphragm due to the more complicated geometrical shape. In this analysis, the fixed regions are treated as the surface; therefore, there is no stress at the base. This circular region is shown in Figure 7. Stress analysis using von Mises's criterion showed that the stress is concentrated at the bottom and top edges. These regions are shown in red in Figure 7.

Table 1. Mechanical properties of the Rayan and Pumpiran rubber diaphragms.

Test name	Standard	Units	Test results
Hardness	ASTM D 2240	Shore A	55±5
Tensile strength	ASTM D 412	N/mm^3	Min. 14
Elongation	ASTM D 412	%	Min. 400
Tear resistance	ASTM D 624	kgf/cm^3	Min. 50
Pressure	ASTM D 395	%	Max. 30
Wear resistance	DIN 53516	mm^3	Max. 140
Resilience	DIN 53512	%	Min. 30

Fatigue test results

To reduce the stress concentration in the Pumpiran rubber diaphragm (Figure 5), two new diaphragms were produced. In the first new sample, the sharp edges were replaced with smooth ones and in the second one the sharp edges were replaced by fully arched edges (Figure 4). The fatigue test results showed drastic reductions in the stress concentration areas due to the fully arched design.

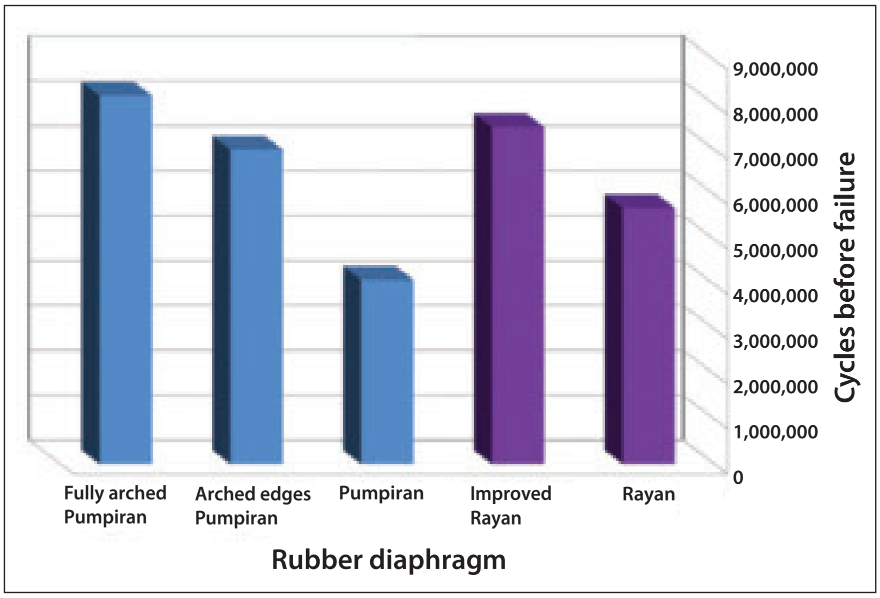

Figure 8. Fatigue life of the different rubber diaphragms as determined by fatigue testing.

This new design leads to significantly improved fatigue life. In the fillet-edged sample, the fatigue life increases by 1.7 times but in the fully arched samples fatigue life almost doubles (Figure 8).

To decrease the areas of stress concentration in the Rayan diaphragm (Figure 7), a new rubber diaphragm of the same composition and with fillet edges was manufactured; the sharp edges were replaced with filleted edges with r = 0.5 cm. Fatigue testing was conducted on the new samples and it was shown that, due to the reduced stress concentration at the edges, the fatigue life of the sample was improved by 1.3 times (Figure 8).

Conclusions

In the first rubber diaphragm (Pumpiran), using the fully arched alternative diaphragm instead of the original design approximately doubles the fatigue life. The main reason for this increase is a large reduction in the stress concentration magnitudes. Moreover, this new design increases the strength of the diaphragm. In the flat- edged diaphragm design, this increase was 1.7 times compared with the original sample. This improvement is due to the reduction in stress concentration magnitude and the replacement of the sharp edges.

In the second rubber diaphragm (Rayan), the new design with the filleted edges increases the fatigue life of the sample by 1.3 times. This increase was due to the reduced stress concentration in the filleted samples. ■

Contact

Amin Akhbarizadeh and Alireza Araghi
Research and Development Dept
Pars Koral Ghomes Co
North Hemmat Avenue
Shiraz 7186655169, Iran
Tel: +98 917 113 4163
Fax: +98 711 631 5142
Email: A.akhbarizadeh@ma.iut.ac.ir