Linear motion feed through with thin wall rubber sealing element

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Abstract. The patented linear motion feedthrough is based on elastic thin rubber walls usage being reinforced with analeptic string fixed in the middle part of the walls. The pneumatic or hydro actuators create linear movement of stock. The length of this movement is two times more the rubber wall length. This flexible wall is a sealing element of feedthrough. The main advantage of device is negligible resistance force that is less then mentioned one in sealing bellows that leads to positioning error decreasing. Nevertheless, the thin wall rubber sealing element (TRE) of the feedthrough is the main unreliable element that was the reason of this element longevity research. The theory and experimental results help to create equation for TRE longevity calculation under vacuum or extra high pressure difference action. The equation was used for TRE longevity determination for hydraulic or vacuum equipment realization also as it helps for gas flow being leaking through the cracks in thin walls of rubber sealing element of linear motion feedthrough calculation.

1. Introduction
The main purpose of the feedthroughs design was long travel three-coordinate drive creation with unique parameters, which are: travel length about 300–500 mm; high pressure till $3 \times 10^5$ Pa or vacuum till $10^{-6}$ Pa; angles of motion stock inclination around $Y, Z$ axis about $3–5^\circ$; gas flow penetration (dissolution) through thin rubber wall less $Q = 10^{-9}$ m$^3$ Pa/s; longevity more $N = 10^6$ cycles. The base element of the feedthroughs is the elastic thin-wall rubber element (TRE) reinforced with analeptic strings being fixed into the middle part or the rubber walls.

2. Feedthrough design
The feedthroughs may be used as in high vacuum equipment, also as in pneumatic and in hydraulic equipment with pressure till two atmosphere [1, 2]. The main advantage of the feedthroughs is the negligible value of the resistance force, which is many times less the resistance forces in metal bellows, membranes, traditional rubber collar sealing elements, being used in pneumatic, hydraulic or in vacuum technology practice. From another side the limited longevity of feedthroughs (TRE) element is the main disadvantage of the drive based on TRE. The patented linear motion feedthrough [3] is based on elastic thin rubber walls usage being reinforced with analeptic string fixed in the middle part of the walls. The scheme of the linear motion vacuum feedthrough is shown in figure 1(a). The elastic rubber wall thickness is about 0.3–0.4 mm and stock diameter is about $D = 20$ mm, as it is shown in figure 1(b).

The TRE longevity research was done on experimental installation, the scheme of which is shown in figure 2.
3. Theoretical base
The theory [1, 2] and experimental results help to create equation for TRE longevity \( N \) calculation under pressure difference action. The equation for TRE means longevity calculation in working cycles:

\[
N = 10^{\frac{\sigma_a - \sigma_0}{3.55}},
\]

where \( \sigma_a \) – TRE amplitude stress, MPa; \( \sigma_0 \) – TRE ultimate strength, MPa (\( \sigma_0 = 30 \text{ MPa} \)).
The equation (1) was used for TRE longevity determination in equipment for variable media technology realization also as it helps for gas flow being leaking through the cracks in thin walls of rubber sealing element of linear motion feedthrough calculation.

The pneumatic or hydro actuators create linear movement of stock. The linear motion feedthrough contains linear moving stock 1, elastic rubber flexible sealing elements 2, and body.

The experiments show, that under condition:

\[ \sigma_0 = \sigma_a \]

where \( \sigma_0 \) – ultimate strength under stretch load, the TRE longevity is equal \( N = 1 \), i.e. the TRE expectable disruption is after first cycle of load. The experimental result show, that for rubber IRP-1345 (RF standard) \( \sigma_0 = 30 \text{ MPa} \).

The TRE longevity research was done on experimental installation (figure 1), where additional pressure in work volume \( 8 \) was about \( p_1 = 0.1 \text{ MPa} \). The mean TRE longevity figure was about \( N = (2.18 \pm 1.28) \times 10^6 \) cycles at mean stress amplitude value \( \sigma = 30 \text{ MPa} \). The scheme and directions of the stresses amplitude \( \sigma \) appearing in TRE we can see in figure 1(b).

The distance \( W \) between inner surface of body 5 hole and stock 1 outer surface (figure 1) plays the main role in circumferential stress forming. Circumferential stress may be calculated

\[ \sigma_{ti} = \frac{pD}{2h} \]

where \( p \) – additional (differential) pressure on TRE wall \( (p = 0.1 \text{ MPa}) \); \( D \) – stock diameter \( (D = 20 \text{ mm}) \); \( h \) – wall TRE thickness \( (h = 0.4 \text{ mm}) \).

Maximal values of circumferential stress \( \sigma_{ti} \) also as pressure difference \( p_1 - p_2 = 0.046 \text{ MPa} \) are realized at \( 2R = W = 3 \text{ mm} \). Axial stress in TRE wall may be calculated

\[ \sigma_{mi} = \frac{p\left[(D + 2W)^2 - D^2\right]}{8Dh} \]

where

\[ W = \frac{pD^2}{2Eh\left(1 - \frac{\mu}{2}\right)} \]

where \( E \) – modulus of elasticity of rubber \( (E = 6 \text{ MPa}) \); \( \mu \) – Poisson’s ratio for rubber \( (\mu = 0.5) \).

Axial stress in TRE wall may be increased till \( \sigma_{mi} = 0.43 \text{ MPa} \) at pressure difference \( p_1 - p_2 = 10^5 \text{ Pa} \) and may be calculated

\[ \sigma = \frac{pR}{2h} \]

\[ \sigma_{au} = \frac{pR \left(2a + R \sin \varphi\right)}{2h \left(a + R \sin \varphi\right)} \]

where \( R \) – radius of TRE being bended; \( \varphi \) – measured angle of TRE being bended.

The calculation shows, that \( \sigma_t = 0.21 \text{ MPa} \) and \( \sigma_{au} = 0.43 \text{ MPa} \) at \( \varphi = 90^\circ \). In our case, maximum stress values were \( \sigma_a = \sigma_{ti} = 1.15 \text{ MPa} \) and for rubber IRP-1345 being used in experimental TRE the stress-longevity equation:

\[ 1.15 + m \lg(2.16 \cdot 10^6) = 30 \]

where constant \( m = 4.55 \text{ MPa} \) and

\[ \sigma_a + 4.55 \lg N = 30 \]

In this case data of equation (7) may be used in the equation (1) for TRE longevity determination in equipment under variable pressure, also as it helps us for gas flow leaking through the thin walls of rubber sealing element calculation.
4. Experimental results
The results of residual pressure variation in sealed chamber after crack in TRE appearing are shown in figure 3. The graphs point $t = 0$ corresponds to experiment beginning after 2000 cycles of TRE service period, and after crack in TRE appearing.

![Graph of residual pressure variation in sealed chamber after crack in TRE appearing, where: 1 – cycle time 8 s; 2 – crack in TRE “open” position.](image)

The experiments show, that in stock position with the crack placed in the bended part of the TRE, the crack is open for leaking gas flow, also as it is closed when the TRE wall is pressed to stock or to body surface. The result of this crack behavior is step-form pressure variation at reciprocal stock linear motion. The gas flow leaking through the crack after periodically opening–closing crack narrow may be calculated:

$$Q_n = \frac{G_t - G_i}{t},$$  

where $G_{t,i}$ – gas amount in the vacuum chamber at the initial moment; $t$ – experimental time (in our case $t = 65$ s). Gas amount in the vacuum chamber at the final moment may be calculated:

$$G_{t,i} = P_{1,t} V,$$  

where $P_{1,t}$ – gas pressure in chamber at final moment; $V$ – chamber volume (in our case $V = 3.31 \times 10^{-3}$ m$^3$). The crack conductivity:

$$U = \frac{Q_n}{P_{av}} = \frac{G_t - G_i}{t \cdot P_{av}} = \frac{V(P_t - P)}{t_{av}},$$  

where $P_{av}$ – gas mean pressure in chamber at time $t$, when the crack is open.

The crack conductivity value may be used for crack conditional diameter calculation:

$$d = \sqrt{\frac{U h}{1360 P_{av}}},$$  

where $h$ – TRE wall thickness ($h = 3.5 \times 10^{-4}$ m). So, taking into account equation (10) and pressure variation according figure 3 graphs, we may use these data for cracks size parameters estimation. The results of mentioned experiments presentation we can see in table 1.

| The cycle number after crack appearing | $P_0$, MPa | $Q_n$, m$^3$ Pa/s | $U$, m$^3$/s | $d$, m |
|----------------------------------------|------------|------------------|---------------|-------|
| 0                                      | 0.127      | 3.72             | 2.84 \times 10^{-5} | 8.64 \times 10^{-5} |
| 2000                                   | 0.108      | 4.68             | 3.69 \times 10^{-5} | 9.3 \times 10^{-5} |
5. Conclusions
The results show, that fatigue crack of the TRE appearing and increasing is being correlated with pressure variation as a result of leaking flow intensity value.

The demanded work pressure may be created, when the TRE crack is pressed to the shaft or to body’s surfaces the gas flow through the crack is equal to zero, because the crack’s tunnel is covered with the wall’s surface in the marked shaft position.

The process of the crack spontaneous “closing” is the advantage of this feedthroughs type because it helps to ensure demanded work vacuum at any moment of the working period with help of shaft stopping the marked shaft position.

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