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Design of the Three Gorges Ship Elevator's Gate Water Seal and Seal's Working Performance Analysis

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Abstract: Based on simulation study of high-pressure gate water seal, we have designed the Three Gorges ship elevator's gate water seal and have analyzed the seal working performance. In the design process, we selected some relatively optimal seal sections and materials firstly and compared with their working performance about dorsal cavity leakproofness, free overhang of seal head, watertight ability of seal head and gate's hoisting force by simulation. Finally, we selected optimal seal section and materials. Before then, to design water seal mainly depended on experience and experiment. The design of the Three Gorges ship elevator's gate water seal has provided a standard design reference based on calculation analysis.

Key words: Water seal, simulation, leakproofness, free overhang, watertight ability, hoisting force

INTRODUCTION

The three Gorges Hydro Project is a crucial backbone engineering which administrates and exploits the Yangtze River of China and has huge multiple benefit from prevent flood, generate electricity and shipping. The Three Gorges ship elevator is a rapid gallery that liner pass the Three Gorges dam and it be located in somewhere between ship gate and 7#, 8# non-overflow dam monolith. The ship elevator consists of upstream approach channel, head bay, ship side room section, tail bay and downstream approach channel and it is about 5000 m long.

The Three Gorges ship elevator uses air pressure retractable water-stop device. The device is composited by water-stop component, pressure source equipment and electrical control equipment. The water-stop component appears U shape and it is fixed on upstream face of gate flap. When gate resists water£¬the water-stop device holds the water pressure. When pressure drops to setting pressure, the pressure source equipment pressurizes. In the process of adjust gate location, the water-stop device decompresses and after the process the pressure source equipment pressurizes again.

In the article, we narrate the design process of the Three Gorges ship elevator's gate water seal and analyze the seal working performance. All the work is to provide a standard design reference based on calculation analysis for air pressure retractable water seal design.

SIMULATION THEORY OF WATER SEAL AND SECTION INITIAL SELECTION

The Simulation Theory of Water Seal: We have excogitated a set of simulation calculation and simulation approximation method about water seal by 10 years research.

The finite element calculation (Alan, 2001; Kuang, 1989; Lei *et al*., 2010; Liu *et al*., 2007, 2011a; Boyce and Arruda, 2000; Nagendrav and Akshantala, 2000; Pidaparti and May, 2001; Yang *et al*., 2011) about water seal refers to material nonlinearity, geometry nonlinearity and contact nonlinearity. We divide the strain ξinto linear part and nonlinear part when calculate. Equation 1 is component expression. In the equation, u is displacement and superscript denote direction and strain is derivatives of displacement with respect to Lagrange material coordinate:

$$\xi_{ij} = \xi_{ij}^{L} + \xi_{ij}^{N} = \frac{1}{2}\left(\frac{\partial u^{j}}{\partial \varepsilon^{i}} + \frac{\partial u^{i}}{\partial \varepsilon^{j}}\right) + \frac{1}{2}\left(\frac{\partial u^{k}}{\partial \varepsilon^{i}}\frac{\partial u^{k}}{\partial \varepsilon^{j}}\right) \tag{1}$$

Use second-order tensor to express sixth dimensions vector, are:

$$\begin{aligned} &\xi = [\xi_{11}, \xi_{22}, \xi_{33}, 2\xi_{23}, 2\xi_{31}, 2\xi_{12}]\xi^{L} = [\xi_{11}^{L}, \xi_{22}^{L}, \xi_{33}^{L}, 2\xi_{23}^{L}, 2\xi_{31}^{L}, 2\xi_{12}^{L}] \\ &\xi^{N} = [\xi_{11}^{N}, \xi_{22}^{N}, \xi_{33}^{N}, 2\xi_{23}^{N}, 2\xi_{31}^{N}, 2\xi_{12}^{N}] \end{aligned} \tag{2}$$

Matrix expressions are:

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Table 1: Material's parameters of water seal

Material parameters	C_{10}	C_{01}	Friction coefficient (contact with steel)	Poisson ratio
Seal head	0.6042	0.5196	0.5	0.4997
Wing tops and limbs	0.2501	0.1802	0.5	0.4997

$$\begin{aligned}\xi^L &= \nabla L u = \nabla L N a_e = B^L a_e \\ \xi^N &= \frac{1}{2}A\theta = \frac{1}{2}AGa_e = B^N a_e \\ \xi &= \xi^L + \xi^N = (B^L + B^N)a_e = \tilde{B}a_e\end{aligned} \quad (3)$$

Among Eq. 3, arithmetic operator:

$$\nabla L = \begin{bmatrix} \frac{\partial}{\partial\varepsilon^1} & 0 & 0 & 0 & \frac{\partial}{\partial\varepsilon^3} & \frac{\partial}{\partial\varepsilon^2} \\ 0 & \frac{\partial}{\partial\varepsilon^2} & 0 & \frac{\partial}{\partial\varepsilon^3} & 0 & \frac{\partial}{\partial\varepsilon^1} \\ 0 & 0 & \frac{\partial}{\partial\varepsilon^3} & \frac{\partial}{\partial\varepsilon^2} & \frac{\partial}{\partial\varepsilon^1} & 0 \end{bmatrix}^T$$

Matrixes:

$$A = \begin{bmatrix} \frac{\partial u^T}{\partial\varepsilon^1} & 0 & 0 & 0 & \frac{\partial u^T}{\partial\varepsilon^3} & \frac{\partial u^t}{\partial\varepsilon^2} \\ 0 & \frac{\partial u^T}{\partial\varepsilon^2} & 0 & \frac{\partial u^T}{\partial\varepsilon^3} & 0 & \frac{\partial u^T}{\partial\varepsilon^1} \\ 0 & 0 & \frac{\partial u^T}{\partial\varepsilon^3} & \frac{\partial u^T}{\partial\varepsilon^2} & \frac{\partial u^T}{\partial\varepsilon^1} & 0 \end{bmatrix}^T \quad \theta = \begin{bmatrix} \frac{\partial u}{\partial\varepsilon^1} & \frac{\partial u}{\partial\varepsilon^2} & \frac{\partial u}{\partial\varepsilon^3} \end{bmatrix}^T$$

$$G = \begin{bmatrix} \frac{\partial N_1}{\partial\varepsilon^1}I_3 & \frac{\partial N_2}{\partial\varepsilon^1}I_3 & \cdots & \frac{\partial N_m}{\partial\varepsilon^1}I_3 \\ \frac{\partial N_1}{\partial\varepsilon^2}I_3 & \frac{\partial N_2}{\partial\varepsilon^2}I_3 & \cdots & \frac{\partial N_m}{\partial\varepsilon^2}I_3 \\ \frac{\partial N_1}{\partial\varepsilon^3}I_3 & \frac{\partial N_2}{\partial\varepsilon^3}I_3 & \cdots & \frac{\partial N_m}{\partial\varepsilon^3}I_3 \end{bmatrix}^T$$

Among matrixes, N is shape function, B^L and B^N are linear part and nonlinear part of Green strain tensor's transition matrix with displacement vector a_e of element's node, G is vector of displacement gradient's transition matrix with a_e.

The finite element calculation of water seal is the solution of integral Eq. 4:

$$a\int_{V_e} B^T D\tilde{B} dV = \int_{V_e} N^T p_0 dV + \int_{A_{e\,\tau}} N^T q_0 dA \quad (4)$$

Flexibility matrix in the article adopt Mooney-Rivlin two parameters model and strain energy function is:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (5)$$

I_1 and I_2 are the first and the second order strain tensor's invariant express by elongation ratio.

The simulation approximation is a method that makes the simulation result unlimited to approach model experiment by an amendment skill. Since, operators keep trying model experiment waste people energy, materials and financial resources, we rectify the deviation of simulation calculation by comparing part of simulation calculation result with model experiment result and capture simulation approximation parameters and use approximation parameters to calculate water seal deformation under other case.

By material property experiment (Yang *et al*., 2011), simulation calculation, comparison about part of simulation calculation result and model experiment result and parameters amendment, we assume the relatively accurate material parameters of water seal material as recorded in Table 1.

Section initial selection: By survey and communication with gate designer, we initially selected two water seal sections as shown in Fig. 1 (China three gorges corporation, 2011).

DORSAL CAVITY LEAKPROOFNESS ANALYSIS OF WATER SEAL

Dorsal cavity leakproofness of air pressure retractable water seal depend on contact stress of compression face of two wing tops. Using abovementioned simulation method and material parameters, we simulated two working condition of two water seal sections-assembly process and 20 m hydraulic head (normal working hydraulic head). The contact stress of wing tops as following.

Assembly process: The contact stress of wing tops during assembly process as shown in Fig. 2.

Section one: When assembly process is completed, the contact stress max of two wing tops and pressing plate is 2.34 MPa and contact stress average value is 1.32 MPa.

Section two: When assembly process is completed, the contact stress max of two wing tops and pressing plate is 4.16 MPa and contact stress average value is 1.52 MPa.

20 m hydraulic head working stage: By simulation research, we acquire following information. Section one: In normal working stage, the contact stress max of two wing tops and pressing plate is 2.88 MPa and contact stress average value is 1.25 MPa. Section two: The contact stress max of two wing tops and pressing plate is

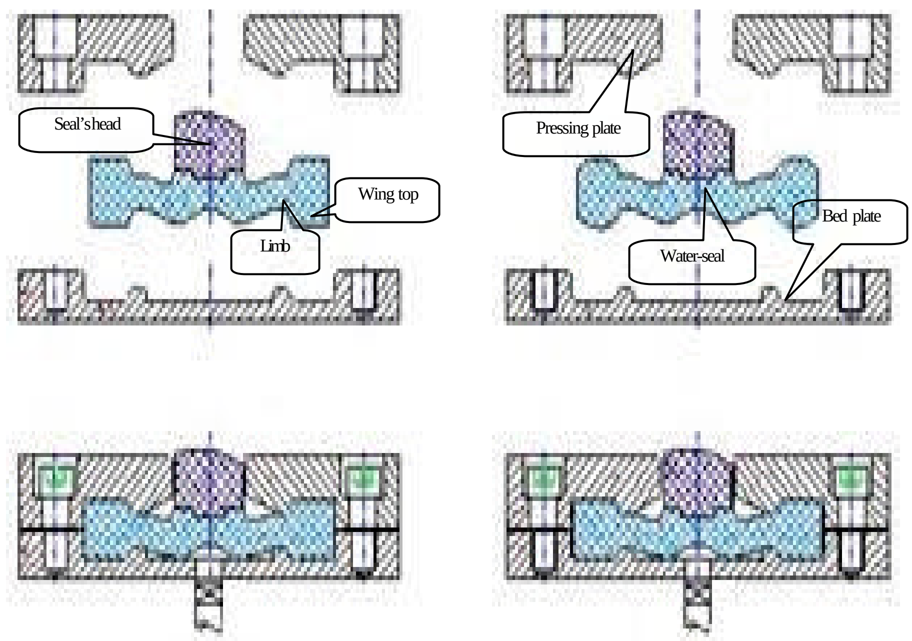

Fig. 1: Two basic sections of water seal

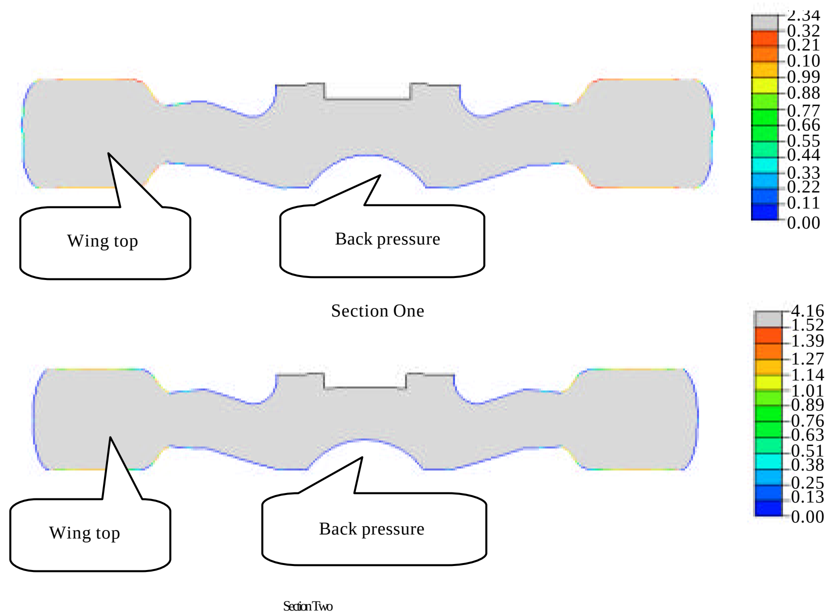

Fig. 2: Wing top's contact stress in assembly process

3.95 Mpa and contact stress average value is 1.45 MPa. All the stress values statistics are far greater than working air pressure on water seal bottom side, therefore whether assembly process or normal working stage the dorsal cavity leakproofness is satisfying.

Comparison of dorsal cavity leakproofness: Water seal section two's contact stress max and average value are greater than section one's in assembly process and normal working stage, therefore section two is superior to section one in dorsal cavity leakproofness.

FREEOVERHANGANALYSISOFSEALHEAD

In order to research the free intumescing mechanics process that seal head move toward water-stop panel, we

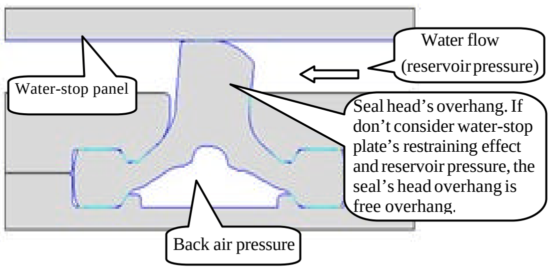

Fig. 3: Analysis model of seal head overhang

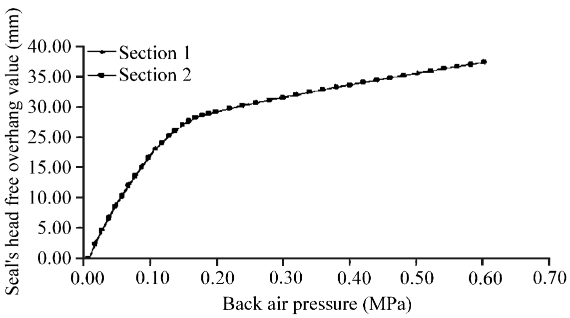

Fig. 4: Curve between seal head free overhang value and back air pressure

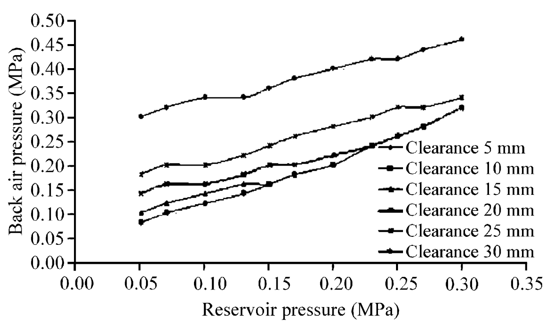

Fig. 5: Corresponding seal back pressure of reservoir pressure curve (section one)

need to simulate water seal's intumescing deformation when seal head has no restrain. Analysis model as shown in Fig. 3 and simulation result statistics as shown in Fig. 4.

According to Fig. 4: I Seal head's free overhang increase when water seal's back air pressure increasing and the relation is nonlinear. II The deviation of seal head's free overhang of two sections is tiny. III Seal head's free overhang appear four features accompany by back air pressure variation: (a) During 0-0.01 MPa, seal head's free overhang value is nearly zero, (b) During 0.02-0.14 MPa, seal head's free overhang value varies sharply and the rapid change is stood at 0.14 MPa. At this time, section one and section two surges to percentage 65.60 and 65.36% elastic deformation, (c) There is a transition area between rapid variation and slow variation of Seal head's free overhang value-during 0.15-0.18 MPa, (d) When back air pressure greater than 0.18 MPa, seal head's free overhang value varied genteelly, the curve between seal head's overhang value and back air pressure appear low slope linear relationship, IV When back air pressure reach 0.30 MPa, seal head's free overhang values of section one and section two are both exceed 30 mm and the values are greater than maximal clearance between seal head and water-stop panel, therefore the seal head's free overhang ability of section one and section two is satisfying.

WATER TIGHTABILITY ANALYSIS OF SEAL HEAD

By simulation research, we can get contact stress and width's variation rule of seal head and water-stop panel when initial clearance value of seal head and water-stop panel are varied. Further, we can get the back air pressure value under different clearance between seal head and water-stop panel when water seal plug up the water flow. Analysis scope: Reservoir pressure are 0.25-0.30 MPa, back air pressure are 0-0.60 MPa and initial clearance between seal head and water-stop panel are 5, 10, 15, 20, 25, 30 mm.

Water seal deformed under joint effect of reservoir pressure and back air pressure and clearance of seal head and water-stop panel. We just take one example-the contact stress and width's simulation analysis result of section one's seal head and water-stop panel are shown in Table 2 and 3.

Simulate contact stress and width of seal head and water-stop panel under joint effect of reservoir pressure and back air pressure and when initial clearance between seal head and water-stop panel are 5, 10, 15, 20, 25, 30 mm.

According simulation result and think of contact stress of seal head and water-stop panel greater or equal reservoir pressure as criterion that water seal plug up the water flow, we can get the back air pressure value when water seal plug up the water flow. The results are shown in Table 4 and Fig. 5.

The difference of section one and section two is the shape of wing tops. By simulation analysis , we know that the shape difference of wing tops doesn't affect watertight ability of seal head , therefore the watertight ability of seal head of section one and section two are not different.

Table 2: Contact width of seal head (reservoir pressure, back pressure and 5 mm clearance)

Contact width Back air (mm) pressure (MPa)	Reservoir pressure (MPa) 0.05	0.10	0.15	0.20	0.23	0.25	0.27	0.30
0.06	-	-	-	-	-	-	-	-
0.08	11.53	-	-	-	-	-	-	-
0.10	14.62	-	-	-	-	-	-	-
0.12	15.97	12.07	-	-	-	-	-	-
0.14	18.15	14.47	-	-	-	-	-	-
0.16	19.68	16.11	14.04	-	-	-	-	-
0.18	20.28	18.12	16.08	-	-	-	-	-
0.20	22.21	20.15	17.10	14.05	-	-	-	-
0.22	22.70	21.17	19.61	17.08	-	-	-	-
0.24	24.25	22.19	20.14	18.09	16.05	-	-	-
0.26	25.26	23.22	22.00	20.11	17.06	16.54	-	-
0.28	26.29	24.95	23.18	20.61	19.08	17.55	16.55	-
0.30	26.79	25.77	24.21	22.75	21.66	20.41	18.59	-
0.32	27.81	26.27	25.57	23.70	22.17	21.12	19.12	19.57
0.34	28.83	27.37	26.72	24.20	23.36	21.65	21.13	20.58
0.36	29.85	28.89	27.27	25.54	24.42	23.25	23.16	21.70
0.38	30.90	29.34	27.77	26.69	25.19	24.35	24.00	22.61
0.40	31.41	29.84	29.02	27.29	26.25	25.19	24.71	23.15

-: Means seal head and water-stop panel haven't contacted

Table 3: Contact stress of seal head (reservoir pressure, back pressure and 5 mm clearance)

Contact stress Back air pressure (MPa)	Reservoir pressure (MPa) 0.05	0.10	0.15	0.20	0.23	0.25	0.27	0.30
0.06	-	-	-	-	-	-	-	-
0.08	0.32	-	-	-	-	-	-	-
0.10	0.42	-	-	-	-	-	-	-
0.12	0.51	0.43	-	-	-	-	-	-
0.14	0.57	0.51	-	-	-	-	-	-
0.16	0.64	0.59	0.52	-	-	-	-	-
0.18	0.69	0.65	0.59	-	-	-	-	-
0.20	0.75	0.71	0.66	0.60	-	-	-	-
0.22	0.80	0.76	0.72	0.67	-	-	-	-
0.24	0.84	0.81	0.77	0.73	0.70	-	-	-
0.26	0.89	0.86	0.82	0.79	0.76	0.73	-	-
0.28	0.93	0.90	0.87	0.84	0.81	0.78	0.76	-
0.30	0.97	0.95	0.93	0.91	0.89	0.87	0.86	-
0.32	1.01	0.99	0.97	0.96	0.94	0.92	0.91	0.88
0.34	1.05	1.03	1.02	1.00	0.99	0.96	0.95	0.93
0.36	1.09	1.07	1.06	1.04	1.03	1.01	1.00	0.98
0.38	1.13	1.11	1.09	1.09	1.07	1.05	1.04	1.03
0.40	1.16	1.14	1.13	1.12	1.11	1.09	1.08	1.07

-: Means seal head and water-stop panel haven't contacted

GATE'S HOISTING FORCE ANALYSIS

On the purpose of selecting appropriate hoist, necessary to analyze the variation rule of gate's hoisting force with back air pressure's change. As gate open and shut need conquer the friction, we need to calculate normal pressure between seal head and water-stop panel and to inquire friction coefficient between rubber material and steel. The calculation method of normal pressure is to calculate the integral of contact stress as what mentioned before. We adopt 0.6 as static friction coefficient between rubber and steel. Gate's hoisting force is normal pressure multiply static friction coefficient.

We simulate two typical working conditions for section one and section two:

- Reservoir pressure is 0.2 MPa, back air pressure is 0.4 MPa and initial clearance between seal head and water-stop panel are 5, 10, 15, 20, 25, 30 mm.The simulation result of maximal static friction between seal head and water-stop panel are shown in Table 5 and Fig. 6
- Reservoir pressure is 0.2 MPa, back air pressure are 0-0.4 MPa and initial clearance between seal head and water-stop panel is 25 mm. The simulation result of maximal static friction between seal head and water-stop panel are shown in Table 6 and Fig. 7

According to Table 5 and Fig. 6, we know the maximal static friction between seal head and water-stop panel is availed decreased with the increase of initial

Table 4: Corresponding seal back pressure of reservoir pressure (section one)

Back air pressure value that water seal Seal the water flow (Mpa)	Initial clearance value between seal head and water-stop panel (mm)					
Reservoir pressure (MPa)	5	10	15	20	25	30
0.05	0.08	0.08	0.10	0.14	0.18	0.30
0.10	0.12	0.12	0.14	0.16	0.20	0.34
0.15	0.16	0.16	0.16	0.20	0.24	0.36
0.20	0.20	0.20	0.20	0.22	0.28	0.40
0.23	0.24	0.24	0.24	0.24	0.30	0.42
0.25	0.26	0.26	0.26	0.26	0.32	0.42
0.27	0.28	0.28	0.28	0.28	0.32	0.44
0.30	0.32	0.32	0.32	0.32	0.34	0.46

Table 5: Maximal static fiction of seal head and water-stop panel (typical working condition one)

Maximal static friction (kN m^{-1})	Initial clearance value between seal head and water-stop panel (mm)					
Section	5	10	15	20	25	30
1	12.14	11.09	9.73	7.83	4.78	0.97
2	12.10	10.97	9.58	7.71	4.68	0.92

Table 6: Maximal static friction of seal head and water-stop panel (typical working condition two)

Maximal static friction (kN m^{-1})	Back air pressure (MPa)								
Section	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40
1	-	0.35	1.10	1.87	2.51	3.08	3.65	4.22	4.78
2	-	0.27	1.01	1.81	2.43	3.00	3.56	4.13	4.68

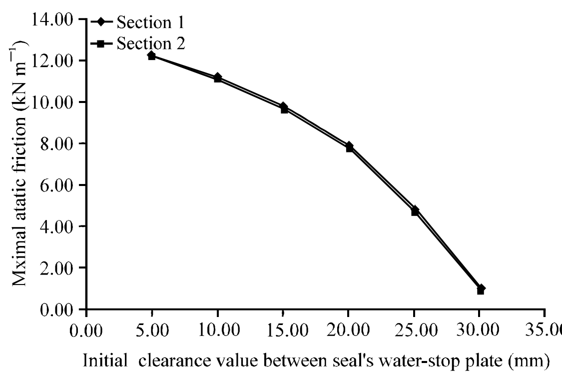

Fig. 6: Curve showing between maximal friction of seal head and water-stop panel (typical working condition one)

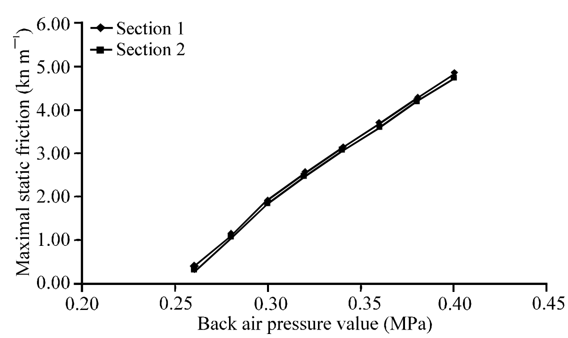

Fig. 7: Curve showing between maximal friction of seal head and water-stop panel (typical working condition two)

clearance value between seal head and water-stop panel when reservoir pressure is 0.2 MPa and back air pressure is 0.4 Mpa. The curve appear nonlinear. The difference of the maximal friction of section one and section two is small and section two's is little less than section one's when clearance value do not change.

According to Table 6 and Fig. 7, we know the maximal static friction between seal head and water-stop panel is amplified with the increase of back air pressure when reservoir pressure is 0.2 MPa and clearance value is 25 mm. The curve appear linear. The difference of the maximal friction of section one and section two is small and section two's is little less than section one's when back air pressure value do not change.

CONCLUSION

The features of the Three Gorges ship elevator gate are low reservoir pressure, large span. Under two sections, which one is superior, we should take following factors into account:

- The maximal principle stress of water seal must be less than the strength of rubber material
- The contact stress of seal wing tops and pressing plate must be as large as possible (dorsal cavity leakproofness requirement)
- The contact stress and width of seal head and water-stop panel must be as large as possible (watertight ability requirement)

- Deformation pattern of water seal is well and stress distribution is homogeneous and avoid stress concentration

We can make following conclusion by simulation analysis and comparison:

- The maximal principle stress of water seal of two sections in the whole stage (assembly and working) is 4.0 MPa, which is less than the strength of rubber material 7.9 MPa, therefore there is no strength fracture of water seal
- In the whole stage, the contact status of wing tops and pressing plate of section one is well and distribution of the contact stress is homogeneous. The contact stress of section two is greater and there is stress concentration on contact face of wing tops. Although, two sections both can seal the water flow, but section two enhances dorsal cavity leakproffness because it uses cabochon contact design. Therefore, section two is superior to section one in dorsal cavity leakproffness
- The difference of seal head free overhang property of two sections is very small. The free overhang values of two sections both exceed 30mm and greater than the maximal clearance between seal head and water-stop panel
- The watertight ability of seal head of two sections are same and they can satisfy requirement of sealing the water flow
- The maximal friction rule of seal head and water-stop panel of two sections are equal, but the maximal friction value of section two is little less than section one

In conclusion, section two is better.

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