ANALYSIS OF ORTHOGONAL DESIGN ON FATIGUE LIFE OF CUP-SHAPED FLEXIBLE GEAR BASED ON ABAQUS AND FE-SAFE

Leyu WEI\textsuperscript{1,2,*} and Changlu WANG\textsuperscript{1,3} Liyong ZHANG\textsuperscript{3} Xinmeng LIU\textsuperscript{3}, Xuetao QIAO\textsuperscript{1,4}, Ruifeng WANG\textsuperscript{3}

\textsuperscript{1}Zhengzhou Research Institute of Mechanical Engineering Co., Ltd., Zhengzhou 450001, China
\textsuperscript{2}North China University of Water Resources and Electric Power, Zhengzhou 450046, China
\textsuperscript{3}Zhengzhou Research Institute of Advanced Equipment & Information Industry Technology Co., Ltd., Zhengzhou 450001, China
\textsuperscript{4}Zhongyuan University of Technology, Zhengzhou 450007, China
E-mail: Email:34323626@qq.com

ABSTRACT: In the harmonic gear drive, the flexible gear is the most easily fatigued and damaged component. In order to improve the fatigue life of the flexible gear, based on the orthogonal design method, this study combines structure parameters of the flexible gear within a certain range to conduct ABAQUS stress analysis and FE-SAFE fatigue life analysis respectively, obtains the length of flexible gear, the thickness of gear ring, the thickness of cup body, the fitting curve of the maximum equivalent stress and fatigue cycle times of the gear width and the gear tooth fillet, range analysis and variance analysis were performed to get the influence of various structural parameters on stress and fatigue life. Based on the analysis results, this study optimizes and selects the parameters, re-establishes the optimization model, and obtains an optimal combination scheme, which provides references for the anti-fatigue design of flexible gear.

KEYWORDS: flexible gear, orthogonal design, finite element, structural parameters, fatigue life

1 INTRODUCTION

Harmonic gear drive is a new type of mechanical transmission that relies on the elastic deformation of the flexible gear to transmit motion and power, because it has the unique advantages of compact structure, large speed ratio, high transmission accuracy and efficiency, stable operation, and low noise, etc., in space technology, conventional weapons, robots and other precision fields, it has been widely used (Yang et al., 2005; Liu et al., 2012).

In power transmission, as a thin-walled component, the flexible gear has periodic deformation under alternating load, and has a large number of engaging tooth. Its deformation law and load distribution are complex. The flexible gear's stress state is very complicated, and these factors would easily lead to fatigue damage of the flexible gear. Basing on the sensitivity analysis method, Deng (2012) obtained the influence law and sensitivity degree of each structural parameter of the flexible gear on the fatigue strength coefficient; Zhao (2013) used the finite element method to study the influence of structural parameters and position accuracy on the stress and fatigue life of the flexible gear.

The stress of the flexible gear is an important factor influencing its fatigue life. This paper combines the orthogonal test design method with the finite element method to analyze the stress of each structural parameters of the flexible gear in a certain range and calculate its life, conduct comprehensive selection of structural parameters to reduce stress and increase fatigue life of the flexible gear.

2 COMPUTATIONAL MODEL OF FATIGUE STRENGTH OF FLEXIBLE GEARS

2.1 Computational model of stress of flexible gear

It is difficult to estimate the influence of the boundary effect of the flexible gear coupling end. At the same time, there are too many pairs of engaging tooth, the load distribution law between the gear tooth and the influence of the gear tooth on the stress distribution in the flexible gear are also difficult to determine, so the establishment of the flexible gear computational model is very
complicated. To simplify the analysis, the analysis of the flexible gear stress is performed using the computational model of the smooth cylindrical shell (Shen and Ye, 1985), and based on the experimental results, further corrections are made. The revised calculation formula for the flexible gear stress is shown as formula (1):

\[
\begin{align*}
\sigma_{G} &= K_M K_d \sigma_0 \frac{\omega_0 E \delta}{r_m^2} \\
\sigma_{\phi G} &= K_M K_d \sigma_\phi \frac{\omega_\phi E \delta}{r_m^2} \\
\tau_{\phi G} &= K_M K_d \sigma_t \frac{\omega_t E \delta}{r_m L}
\end{align*}
\]

(1)

Where, \(v\) and \(E\) are respectively the material Poisson's ratio and elastic modulus, \(\delta, r_m, \omega_0\) are respectively the thickness of the shell, midline radius, and radial deflection, \(\sigma_0\) and \(\sigma_t\) are respectively the normal stress coefficient and the shear stress coefficient, \(K_M\) and \(K\) are respectively the stress growing coefficient and dynamic load coefficient caused by distortion of flexible gear.

2.2 Computational model of fatigue life of the flexible gear

Fatigue failure generally experiences three stages: crack generation, crack growth, and unstable crack growth and fracture. It is a process in which fatigue damage gradually accumulates. The analytical method to determine the fatigue life is based on the fatigue properties of the material, the load history of the structure and the analytical model.

In fatigue cumulative damage theories, the most representative one is the Miner's rule (Yao, 2003). If the component is under a constant stress \(S\), and its life cycle to failure is \(N\), then we define the damage in the \(n\)-th cycle as:

\[D = n / N\]

(2)

Under the effect of stress \(S_i\), the damage of the component is \(D_i = n_i / N_i\) after the \(n_i\)-th cycle. If under the effect of \(k\) \(S_i\), after undergoing \(n_i\)-th cycle respectively, the total damage is:

\[D = \sum_{i=1}^{k} n_i / N_i\]

(3)

The damage rule is:

\[D = \sum_{i=1}^{k} D_i = 1\]

(4)

3 ORTHOGONAL DESIGN AND FINITE ELEMENT ANALYSIS

The structural parameters of the flexible gear mainly include length \(L\), tooth width \(B\), gear tooth fillet \(R\), gear ring thickness \(\delta\), and cup thickness \(\delta_1\). These parameters affect the flexible gear stress together. Since there are many structural parameters, and the parameters have multiple levels, if each combination level is analyzed once, the number of analyses will inevitably greatly increase, therefore, this paper uses the orthogonal design method to arrange the finite element analysis.

3.1 Selection of structural parameter range of flexible gear and the design of orthogonal table

Taking the flexible gear structural parameters in a certain type of harmonic reducer as the prototype, five discrete values are selected for each parameter. In the case of satisfying statistical accuracy, the L_{25} (5\(^6\)) six-factor five-level orthogonal design table (Dong et al., 2013) is selected, where the five structural parameters have five discrete values, respectively, no parameter has been arranged for the remaining one factor so that it would be used for error analysis, 25 analyses were required, the orthogonal table generated in SPSS is shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Length/mm</th>
<th>Gear ring wall thickness/mm</th>
<th>Cup thickness /mm</th>
<th>Tooth width/mm</th>
<th>Gear tooth fillet/mm</th>
<th>Error column</th>
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<td>12</td>
<td>4</td>
<td>2</td>
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<tr>
<td>2</td>
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<td>0.65</td>
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<td>8</td>
<td>4</td>
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<tr>
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<tr>
<td>4</td>
<td>25</td>
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<td>13</td>
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</tr>
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<td>11</td>
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<td>5</td>
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<td>6</td>
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<td>0.75</td>
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<td>11</td>
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<td>0.85</td>
<td>0.5</td>
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<td>4</td>
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<tr>
<td>11</td>
<td>31.5</td>
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<td>0.85</td>
<td>0.55</td>
<td>10</td>
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<td>13</td>
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<td>0.85</td>
<td>0.6</td>
<td>9</td>
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</tbody>
</table>
3.2 Finite element model

Harmonic gear drive is mainly composed of flexible gear, rigid gear and wave generator. If the established contact model has tooth features, then the divided grid, memory occupancy, and calculation duration for analysis will be greatly increased. Therefore, equivalent processing should be conducted to the gear tooth of the flexible gear, and the equivalent method is to simplify the tooth ring of the flexible gear into a smooth ring with a certain thickness, and the equivalent wall thickness of the ring gear is \( \sqrt{1.67} \) (Tuttle and Seering, 1993; Xin, 2003) times the wall thickness of the smooth ring at the tooth root.

![Figure 1. Finite element model ((a) Geometric model; (b) Physical model in the SolidWorks)](image)

Usually, the wave generator is a flexible thin-walled bearing. In order to increase the calculation speed, the wave generator needs to be regarded as a rigid body and replaced by an elliptical wave generator having the same outer contour as the outer wall of the flexible thin-walled bearing (Gao et al., 2010). The long axis of the elliptical wave generator is \( d_z + 2o_0 \) m, and the short axis is \( d_z - 2o_0 \) m, where \( d_z \) is the inner curve of the flexible gear, \( o_0 \) is the radial deformation coefficient, which takes 1 in this paper, \( m \) is the modulus. The established model is shown in Figure 1.

![Figure 2. Meshing ((a) Flexible gear mesh with teeth before equivalent processing; (b) Flexible gear mesh after equivalent processing)](image)

3.3 Finite Element Analysis

Through the data interface, a universal format model is introduced in ABAQUS, and the section properties and material properties are defined. The flexible material is 42CrMo, its elastic modulus \( E = 2.06 \times 10^5 \) MPa, Poisson's ratio \( \mu = 0.3 \), and density = 7850 kg/m\(^3\). Defining the outer cylinder surface of the elliptical generator and the inner cylindrical surface of the flexible gear as the contact surface-pair, in which the outer cylinder surface of the generator is the principle contact surface, and the inner cylindrical surface of the flexible gear is the subordinate contact surface. Meshing by the subdivision of the entity, as shown in Figure 2. In ABAQUS, different load steps can be set to distinguish the precedence relationship between the contact and the load; all the degrees of freedom of the inner cylinder surface of constrained wave generator and the surface of the flexible gear cup bottom take the elastic deformation caused by the contact of the flexible gear and the wave generator as the first analysis step, then add the load in the second step by imposing a torque of 54 N·m to the node on the equivalent cylindrical surface of the flexible gear.

3.3.1 Verification of the correctness of the equivalent model

Since the flexible gear ring is simplified in this paper, it is necessary to verify the consistency of the finite element analysis results before and after they
are simplified. Before and after the equivalent processing, the finite element analysis results are shown in Figure 3a and 3b, respectively, we can know that, before the equivalent processing, the maximum equivalent stress is 558.6 MPa, after the equivalent processing, the maximum equivalent stress is 555.9 MPa. The two values are very close, the error before and after the equivalent processing is 0.5%. The maximum values of the equivalent stress occur at the root of the tooth near the bottom of the cup. The distribution and change trend of the stress cloud are very similar. Therefore, the equivalent simplification of the model is correct.

3.3.2 Finite Element Analysis of Each Group of Models

According to the order in the orthogonal table, the corresponding model was established with each row of parameters and ABAQUS analysis was performed on them respectively. The displacement, stress, and other data of the 25 models were obtained. The equivalent stress of No.19 is shown in Figure 4a; The result file is imported into FE-SAFE, and the stress, strain, load characteristics and other data are selected, and the SAE4140 material similar to the domestic 42CrMo material is specified in the material library for fatigue analysis. The fatigue data corresponding to No.19 can be obtained, as shown in Figure 4b, 4c, 4d. The obtained data of the maximum equivalent stress and the number of fatigue cycles S are shown in Table 2.
4.1 Stress and life Analysis

The mechanical model of the flexible gear is based on the elastic shell theory and is in an alternating stress state. It bears circumferential normal stress, axial normal stress and shear stress. The axial normal stress is relatively smaller compared to the circumferential stress, and can be neglected, namely the flexible gear receives the circumferential normal stress and shear stress caused by the bending moment. The length of the flexible gear, the wall thickness of the gear ring, the thickness of the cup, the width of the tooth, and the gear tooth fillet are the main parameters affecting the stress and fatigue life of the flexible gear. Therefore, it is necessary to analyze each parameter to study the influence degree of each parameter on the stress and life of the flexible gear.

4.1.1 Influence of length on stress and life

The length of the flexible gear has an important influence on the stress and life. The greater the length, the smaller the influence of the boundary constraint on the stress of the gear ring. Discrete values of length analysis in this paper are 19, 25, 31.5, 38, and 44 mm (length to diameter ratios are 0.3, 0.4, 0.5, 0.6, and 0.7, respectively). According to the stress and life data obtained in Table 2, average the results of different analyses at the same level, and conduct polynomial fitting of each level and the mean value (Yang et al., 2006), the resulting fitting curves are shown in Figure 5a, 5b, respectively, we can see that the maximum equivalent stress decreases with the increase of the length to diameter ratio, when the length to diameter ratio increases from 0.3 to 0.5, the maximum equivalent stress decreases rapidly. When the length to diameter ratio increases from 0.5 to 0.7, the decreasing trend of the maximum equivalent stress becomes gentle. The Log value of the number of fatigue cycles S increases with the length to diameter ratio, and the growth trend is approximately linear within the sampling range (Sun et al., 2015; Oleksik and Cofaru, 2017).
4.1.2 Influence of gear ring wall-thickness on stress and life

The analysis range of the gear ring wall-thickness is 0.65-0.85. The mean value of different analysis results of the same level is used for data fitting, as shown in Figure 6. It can be seen from Figure 6a that the influence of the wall-thickness of the gear ring on the maximum equivalent stress is not monotonous, the stress reaches a maximum around 0.70 mm, and then reaches a minimum value around 0.80 mm, and then it rises again. It can be seen from Figure 6b that the Log value of the cycle number S decreases monotonously with the wall-thickness of the gear ring, falling rapidly within the range of 0.65-0.70 mm, sloping down decreasing in the range of 0.70-0.80 mm, and rapidly decreasing after 0.80 mm.

Figure 6. Curve of gear ring wall-thickness, stress and life

4.1.3 Influence of cup thickness on stress and life

The analysis range of the cup thickness is 0.45-0.65 mm, according to the analysis results, the data is fitted. As shown in Figure 7, the maximum equivalent stress value fluctuates within a small range with the increase of the thickness of the cup body. Smaller values appeared near 0.45 mm and 0.60 mm; the number of cycles showed a trend of slow growth followed by a rapid decline, with a maximum value appeared at 0.6 mm.

Figure 7. Curve of cup thickness, stress and life

4.1.4 Influence of tooth width on stress and life

The analysis range of the tooth width is 9-13 mm. The obtained stress and life curve is shown in Figure 8. It can be seen that when the tooth width is smaller and larger, the stress increase trend is not obvious, but in the range of 10-12 mm, the stress growth trend is relatively faster; the number of fatigue cycles decreases monotonously with the increase of tooth width, and in the range of 9-12.5 mm, it is approximately linear, while the tooth width is more than 12.5 mm, the decreasing trend is gentle.
4.1.5 Influence of gear tooth fillet on stress and life

The analysis range of the gear tooth fillet is 0-8mm, and the obtained stress and life curves are shown in Figure 9, respectively. It can be seen that the maximum equivalent stress fluctuates within a small range, and the stress value increases with the increase of the gear tooth fillet. The stress value increases first and then decreases, and at last tends to be stable. When the gear tooth fillet is 4mm, the maximum stress appears. When the gear tooth fillet is in the range of 0-4mm, the influence on the number of cycles is greater, the change in the number of cycles in the range of 5-8mm is not obvious.

![Figure 8. Curve of tooth width, stress and life](image)

![Figure 9. Curve of gear tooth fillet, stress and life](image)

4.2 Range and Correlation Analysis

The influence of the five structural parameters of the flexible gear on stress and life is different. Under normal circumstances, the mean value of the test results of each parameter at different levels can be used for examination, however, in order to determine the degree of influence of each parameter, it is necessary to perform range analysis and correlation analysis.

<table>
<thead>
<tr>
<th>Parameter Analysis items</th>
<th>A(L)</th>
<th>B(δ1)</th>
<th>C(δ)</th>
<th>D(B)</th>
<th>E(R)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value k_{1j}</td>
<td>837.4</td>
<td>459.2</td>
<td>460.8</td>
<td>399.5</td>
<td>482.8</td>
<td>472.4</td>
</tr>
<tr>
<td>Mean value k_{2j}</td>
<td>535.8</td>
<td>511.7</td>
<td>523.4</td>
<td>428.4</td>
<td>504.6</td>
<td>511.6</td>
</tr>
<tr>
<td>Mean value k_{3j}</td>
<td>419.1</td>
<td>522.6</td>
<td>455.3</td>
<td>492.0</td>
<td>522.9</td>
<td>445.0</td>
</tr>
<tr>
<td>Mean value k_{4j}</td>
<td>352.2</td>
<td>473.8</td>
<td>517.4</td>
<td>560.2</td>
<td>485.6</td>
<td>542.0</td>
</tr>
<tr>
<td>Mean value k_{5j}</td>
<td>305.6</td>
<td>482.8</td>
<td>493.2</td>
<td>570.0</td>
<td>454.2</td>
<td>479.1</td>
</tr>
<tr>
<td>Range R</td>
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<td>62.6</td>
<td>170.5</td>
<td>68.7</td>
<td>97</td>
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<tr>
<td>K_{1j}^2</td>
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<td>3990006</td>
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<td>K_{2j}^2</td>
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<td>5157441</td>
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<td>6016973</td>
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<td>6016232</td>
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<td>Deviation Q_{j}</td>
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<td>13982.84</td>
<td>19666.44</td>
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<td>F Value F_{j}</td>
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<td>0.70</td>
<td>4.15</td>
<td>0.47</td>
<td></td>
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</table>
Where $k_{ij}$, $k_{jl}$, $k_{kj}$, $k_{kj}$, $k_{lj}$ are respectively the mean value of the analysis result of parameter $j$ ($j$ can be A, B, C, D, E) at the same level, $K_{ij}$ is the sum of the analysis results of a parameter at one level, $U_j = \sum_{i=1}^{5} K_{ij}^2 / 5, Q_j = U_j - (\sum_{i=1}^{5} k_{ij})^2, F_j = Q_j / Q_{error}$.

From Table 3 and Table 4 we can know that, the ranges are: $R_A > R_D > R_B > R_E > R_C$, namely the influence of each parameter on the stress and fatigue life from large to small are: length, tooth width, gear tooth fillet, gear ring wall thickness, cup thickness. For the maximum equivalent stress, when given $\alpha=0.05$, by table lookup we can get $F_{\text{eq}}=(4.4)=6.39$, while $F_A=32.15>6.39$, at this time, only the length has significant influence on the stress; When $\alpha=0.10$, $F_{\text{eq}}=(4.4)=4.11$, there is $F_A=32.15>F_D=4.15>4.11$, and at this time, both length and tooth width have significant influences on the stress; in contrast with length and tooth width, the gear ring thickness, cup thickness, and the gear tooth fillet have no significant influence on the stress within the selected parameters. Therefore, by variance analysis, the degree of influence of obtained parameters is: $L > B > R \approx R \approx D > C$. For the fatigue life, when given $\alpha=0.05$, by table lookup we get $F_{\text{eq}}=(4.4)=6.39$, while $F_A=325.13>F_D=55.67>6.39$, at this time, both the length and the tooth width have significant influences on the fatigue life; the gear ring wall thickness and the cup thickness have no significant influence on the fatigue life within the selected parameters range, the gear tooth fillet $F_B=3.15$ and $F_{\text{eq}}=(4.4)=6.39$ are relatively close to each other, so the influence degree of various parameters obtained from analysis of variance on the fatigue life is $L > B > R > \delta \approx \delta 1$.

### 4.3 Selection of structural parameters

![Figure 10. Analysis result cloud after optimization](image)

Reasonable selection of various structural parameters can significantly increase the fatigue life of the flexible gear. The length has a significant influence on the fatigue life of the flexible gear. If the length is too long, the volume will increase and the torsional stiffness will decrease. If the length is too short, the stress at the root of the tooth will be increased and it will not be conductive to life, after comprehensive consideration, we choose the length as 31.5mm, at this time the length diameter ratio is
about 0.5. According to the influence of parameters in passage 3.1 on the stress and life, the tooth width is selected as a smaller value of 9mm, the gear ring wall thickness is selected as 0.75mm, the cup thickness is selected as 0.55mm, and the gear root fillet is selected as a larger value of 8mm. After the parameters are determined, the finite element analysis is performed again and the maximum equivalent stress value is obtained as 307.8MPa, the Log value of cycle number S was 6.25, and the minimum value of the safety factor was 0.85, as shown in Figure 10. Compared with the other five groups of data with a length of 31.5mm, the stress value is reduced, and the number of cycles and the minimum safety factor are increased.

5 CONCLUSION

By combining the finite element method with the orthogonal design method, this paper uses fewer analysis to respectively studied the structural parameters of flexible gear, including length, gear ring wall thickness, cup thickness, tooth width, gear tooth fillet about their influence on the stress and fatigue life of the flexible gear, among which the influence of length and tooth width on the stress and fatigue life of the flexible gear is obvious and monotonic; within the selected parameters, the influence of the gear ring wall thickness, the cup thickness, and the gear tooth fillet on the stress and fatigue life fluctuates in a small range.

Range analysis and variance analysis of the orthogonal data of each structural parameter were performed. Within the range of selected parameters, the influence degree of each parameter on the fatigue life of the flexible gear was obtained from large to small as follows: length, tooth width, gear tooth fillet, gear ring wall thickness, cup thickness. Among which, when \( \alpha=0.05 \), the length and tooth width have a significant influence on the fatigue life of the flexible gear. The F value of the gear tooth fillet is less than \( F_{0.05} \), but it is quite close, its influence on the fatigue life is non-ignorable; the gear ring wall thickness and the cup thickness are in the same order of magnitude, both are far less than \( F_{0.05} \), and have no significant influence on fatigue life.

At the same time, the structural parameters were optimized and selected to improve the fatigue life of the flexible gear, which provided references for flexible gear anti-fatigue design.

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7 REFERENCES