Stress analysis and design of the waveguide bellows for EAST ECRH system

Liyuan Zhang¹,²,³, Xiaojie Wang¹, Fukun Liu¹, Handong Xu¹, Dajun Wu¹ and Yunying Tang¹

¹ Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China;
² University of Sciences and Technology of China, Hefei 230026, China
³ Email: zhangly@ipp.cas.cn

Abstract. A 140GHz 4MW long pulse ECRH system for the experimental advanced superconducting tokamak (EAST) has launched in 2011. The waveguide (WG) bellows is an important component in transmission lines, which can absorbs the axial deformation caused by thermal expansion. The flexible WG inside WG bellows dominates bellows performance. In this paper the mechanical analysis including stress analysis and error analysis for flexible WG is presented in detail. A prototype of the WG bellows has been designed and fabricated.

1. Introduction
In the field of magnetic confinement fusion, the Electron Cyclotron Resonance Heating (ECRH) is one of the most effective auxiliary heating methods for plasma [1, 2]. A 140GHz 4MW long pulse ECRH system for EAST is under construction [3, 4]. The whole transmission lines is mainly consist of four independent 63.5-mm-diameter aluminum alloy corrugation WG, each carries 1MW microwave power from gyrotron to launcher. The length of each line is up to 30m due to the distance between gyrotron and the EAST vacuum vessel. For non-ideal conductor aluminum alloy, power loss on components is unavoidable, so each transmission line must be equipped at least one WG bellows to match thermal expansion and contraction [5, 6].

There are two different WG bellows structures on ECRH system, as shown in Figure 1 [7, 8]. One is a sliding joint bellows, using a sleeve over two separated sliding WGs, the other one is a flexible WG under the special couplings. The flexible WG with thin-walled section machined directly in aluminum alloy, is a core unit of the second WG bellows, which will be used on ITER, but the principle and the design details report are few. So this paper will focus on research of the flexible WG from stress analysis, combined with the theory of microwave propagation.

In Section 2, several suitable parameter sets are proposed by using the microwave propagation theory. In Section 3, the optimum parameter is designed based on stress analysis. In Section 4, the manufacture of the flexible WG and prototype bellows. A conclusion is presented in Section 5.

2. Microwave propagation analysis
In cylindrical coordinate in Figure 2, the microwave propagates along z direction, and w, h and p are the corrugation width, depth and period respectively. When the inner diameter $d$ ($d = 2r$) is much bigger than the wave length $\lambda$ of 140GHz EC wave, and $\lambda \gg 2p$, the electromagnetic characteristics can be described by surface-impedance method. The surface-impedance $Z$ of WG inner can be represented approximately as
where \( k = \frac{2\pi}{\lambda} \). The corrugated WG will support HE_{11} mode with lowest ohmic loss when the value of \( Z \) approaches infinity [9]. So the corrugation depth of the WG should be chosen as:

\[
h = \frac{\lambda}{4} (1 + 2n), \quad n = 0, 1, 2, 3, \ldots
\]

(2)

Figure 1. Two types of WG bellows for ECRH system.

Figure 2. Schematic structure of the flexible WG.

The groove depth \( H \) of flexible WG shall be in accordance with Eq.2. When \( n \leq 3 \), the flexible structure has no flexibility, and when \( n > 7 \), the manufacture is very difficult. The operating frequency of EAST ECRH is 140GHz, and the WG sizes satisfy the over-mode requirement described above. According to the above principles, some possible values of \( H \) are listed in Table 1.

| \( n \) | 4 | 5 | 6 | 7 | \( \ldots \) |
|-------|---|---|---|---|---------|
| \( H/mm \) | 4.82 | 5.90 | 6.96 | 8.04 | \( \ldots \) |

Table 1. Possible values of the flexible WG groove depth.

To void the Braggs reflection, the period \( p \) should be less than half a wavelength. Combining the parameters of corrugation WG in Ref. [10], the groove width \( W \) should meet: 0.5 mm \( \leq W \leq 0.8 \) mm. Then the suitable parameter sets by electromagnetic analysis are listed in Table 2.
3. Mechanical analysis

3.1. Finite Element Model

When the ECRH system is on operation, the flexible WG will be always compressed, the force direction on axisymmetric flexible WG is axial. So the finite element mechanical analysis for flexible WG can be regarded as an axisymmetric problem [11, 12]. The simplification from 3D to 2D model will reduce the requirements for computer hardware and save computation time. The 3D and 2D model are shown in Figure 3. In this paper the 2D models will be meshed with 4-node element.

Table 2. List of suitable parameter sets.

| H/mm | W/mm  | 0.5   | 0.6   | 0.7   | 0.8   |
|------|-------|-------|-------|-------|-------|
| 4.82 | No.4-1| No.4-2| No.4-3| No.4-4|
| 5.90 | No.5-1| No.5-2| No.5-3| No.5-4|
| 6.96 | No.6-1| No.6-2| No.6-3| No.6-4|
| 8.04 | No.7-1| No.7-2| No.7-3| No.7-4|

![Figure 3. Finite element analysis model.](image)

3.2. Stress analysis

When the U-like flexible WG, shown in Figure 3(b), is compressed, the maximum stress will occur at the bottom corner of the U-shape, there are the bending stress which causes by the bend around the corner and membrane stress due to the tension-compression deformation. So the stress evaluation of the flexible WG can refer to the JB 4732-1995 Steel Pressure Vessels – Design by Analysis [13], but the stress should be classified by equivalence principle. Equivalent linearization of stress as shown in Figure 4, is an effective method for stress classification [14]. It stipulates that the allowable value of primary membrane stress ($\sigma_m$) plus primary bending stress ($\sigma_b$) intensity is $1.5 \cdot K \cdot [\sigma]_m$:

$$\sigma_c + \sigma_s = \sigma_m \leq 1.5 \cdot K \cdot [\sigma]_m$$  \hspace{1cm} (3)

where $K=1$, is a factor of load combinations, and the $[\sigma]_m$ is allowable stress value of the materials. Aluminum alloy 6061-T6 with low density, high strength, excellent electrical and thermal conductivity, has been used as WG material on EAST ECRH system. The higher strength aluminum alloy 7075-T7351, is another alternative material for flexible WG.
In Figure 5, it shows the dependences of $\sigma_{III}$ on the parameters of flexible structure, which analyzed through the FEA software. It is clear that the $\sigma_{III}$ will go down by the depth increasing, and will go up with the width wider. However, the 6061-T6 cannot meet the strength requirement of flexible WG, and the 7075-T7351 is possible to satisfy the requirement if the grooves depth up to 6.96mm.

![Figure 4. Equivalent linearization of stress for group No.4-1.](image)

![Figure 5. Dependences of $\sigma_{III}$ on the parameters of flexible structure.](image)
3.3. Error analysis
Machining errors are unavoidable. The flexible WG deep grooves will be machined by customized cutters, so the width error of the grooves could be ignored. However, it is possible that the grooves deviated to one side along the width as shown in Figure 6. The offset of the grooves will result in the increasing of stress intensity. The Figure 7 shows that the bigger deviations, the greater $\sigma_{III}$. When the depth $H$ is 6.96 mm, the deviation $o$ should be up to 0.05mm, and when $H$ is 8.04 mm, the deviation $o$ could up to 0.05mm or more, so it could reduce the difficulty of processing.

![Figure 6. Definition of dimensional deviation.](image1)

![Figure 7. Dependences of $\sigma_{III}$ on the deviation.](image2)

4. Design and manufacture
Based on the comprehensive analysis of the effect of mechanical stress and thermal stress, the smaller stress intensity group No.7-2 is selected for flexible structure parameters. Referring to Ref [8] and [9], the design of WG bellows has been completed, as shown in Figure 8, including WG coupling, cooling structure and the core flexible WG. The prototype shown in Figure 9 has been finished after overcoming several technical challenges as follows:

a) The waveguide corrugations are tiny;
b) The grooves of flexible structure are deep and narrow, and the walls are thin;
c) Two kinds of the grooves with different period intertwine together.
5. Conclusions
The principle of flexible WG structure has been analysed based on the theory of microwave propagation. The details of stress analysis and simulation for flexible WG are provided with finite element. The WG bellows prototype for EAST ECRH is designed and manufactured. The test work is under preparation.

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