THE EFFECT OF SLOT NUMBER IN WORKING PERFORMANCE OF A BLOCK-LIKE HORN USED IN PLASTICS ULTRASONIC WELDING

Dang Anh Tuan, Nguyen Thi Bich Ngoc, Nguyen Ngoc Thieu, Nguyen Dinh Ngoc*
TNU - University of Technology

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ABSTRACT

A horn is an important part of the ultrasonic plastic welding system. The design characteristics of the horn will directly affect the quality of the weld. This study aims to analyze the influence of the number of slots in the two directions of the block-like horn on the working performance of the horn. Two analysis techniques are used such as modal and harmonic analysis. The finite element method is utilized to perform the two analysis steps mentioned above. The results show that under the direct influence of the Poisson effect, the use of longitudinal slots significantly improves the uniformity of the displacement on the working profile and reduces the maximum stress generated in the horn. In particular, the number of slots also has a direct influence on the uniformity of the profile, the spacing of the frequency separation and the maximum stress generated. The research results of this paper can be considered the first important results, aiming to orient the coming research on developing optimization methods for block-like horns with complex working profiles for industrial applications.

SỰ ẢNH HƯỞNG CỦA SỐ LƯỢNG RÃNH LÊN HIỆU SUẤT LÀM VIỆC CỦA ĐẦU HÀN DẠNG KHỐI SỬ DỤNG TRONG HÀN SIÊU ÂM NHỰA

Đặng Anh Tuấn, Nguyễn Thị Bích Ngọc, Nguyễn Ngọc Thiệu, Nguyễn Đình Ngọc*
Trường Đại học Kỹ thuật Công nghiệp - ĐH Thái Nguyên

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TỪ KHÓA

Hàn siêu âm
Thiết kế đầu hàn
Đầu hàn dạng khối
Độ đồng đều chuyển vị
Phương pháp phần tử hữu hạn

TÓM TẮT

Đầu hàn là một bộ phận rất quan trọng trong hệ thống hàn siêu âm nhựa. Các đặc điểm thiết kế của nó sẽ ảnh hưởng trực tiếp tới chất lượng mối hàn. Nghiên cứu này nhằm mục đích phân tích sự ảnh hưởng của số lượng rãnh trên hai phương của đầu hàn dạng khối lên hiệu suất làm việc. Hai kỹ thuật phân tích được sử dụng là phân tích phương thức và sóng hài. Phương pháp phần tử hữu hạn được sử dụng như một công cụ để thực hiện hai bước phân tích nêu trên. Kết quả cho thấy rằng, dưới ảnh hưởng trực tiếp của hiệu ứng Poisson, việc sử dụng các rãnh dọc trục có tác dụng cải thiện đáng kể độ đồng đều chuyển vị trên biên dạng làm việc và làm giảm ứng suất lớn nhất phát sinh trong đầu hàn. Đặc biệt, số lượng rãnh cũng có ảnh hưởng trực tiếp tới độ đồng đều biên dạng, khoảng cách về độ phân tách tần số và ứng suất lớn nhất phát sinh. Kết quả nghiên cứu của bài báo này có thể coi là những kết quả quan trọng đầu tiên, nhằm định hướng cho các nghiên cứu tiếp theo về việc phát triển các phương pháp tối ưu đầu hàn dạng khối có biên dạng làm việc phức tạp ứng dụng trong công nghiệp.

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* Corresponding author. *Email: ngocnd@tnut.edu.vn*

1. Introduction

Ultrasonic plastic welding is an advanced method of connecting plastic parts through the use of ultrasonic energy. This process uses high-frequency sound waves to create friction and heat at the contact surfaces of plastic parts, causing the parts of the solder to melt and fuse together [1] – [3]. Typically, a plastic ultrasonic welding system consists of main parts summarized as follows. The first part is the transducer, which converts the electrical energy into ultrasonic energy and creates high-frequency ultrasonic vibrations to weld and bond plastic materials. Next is the booster, which is an intermediate part between the transducer and the horn, amplifying the amplitude of the ultrasonic vibrations from the transducer before they are transmitted to the horn. To achieve good weld quality, the initial displacement excited from the transducer should be amplified to obtain better displacement at the end of the working zone [4] – [6]. The horn or sonotrode is the final part of the system where the ultrasonic vibrations are focused and transmitted into the material to be welded. Horns often have special designs and shapes to optimize weld quality and performance. In some cases, the horn and booster may be attached to each other. Fixture is the part that holds the plastic samples to be welded in the correct position and ensures even pressure in the welding process [7] – [8].

Among the above components, the horn is a very important detail in the ultrasonic welding system because it directly affects the energy transfer efficiency, weld quality, and longevity of the system. In the block-like horn design process, it is required attention to many factors to ensure optimal performance and weld quality [9] – [11]. Proper horn design and fabrication is the key to ensure the success of the ultrasonic welding process. Normally, the following four factors are very important, affecting the quality of horn performance. The first standard is the displacement uniformity of the working surface on the horn. The second is the frequency separation between longitudinal frequency and other frequency modes. The third standard is that to achieve welding efficiency and good weld quality, the axial amplitude should be the largest. And finally, the stress generated inside the horn body is always less than the endurance limit to ensure the horns not to be broken during work. There have been a few studies on the design and optimization of blade-like horns with simple working profiles, such as straight-line profiles or flat profiles, so far [12], [13]. However, there have not been any studies related to block-like horns with working surface profiles in the form of complex profiles. Therefore, it can be said that this is a gap in the research community that needs to be paid more attention.

This study aims to present some important preliminary results related to the optimal design of block-like horns with complex working profiles. The finite element method, through Abaqus software, is used as an effective tool to analyze the mode shape, the frequency separation between longitudinal natural mode and the ones which are pre and post. The uniformity of the displacements on the working profile is also analyzed and evaluated through the results from harmonic analysis. The research results of this paper contribute to building the foundation for developing a future optimal design method for block-like horns serving the ultrasonic welding of complex-shaped welds in the automotive, children's toy, and printing industry, etc.

2. Method of designing the block-like horn

The welding considered in this study is a turn signal made of Acrylonitrile Butadiene Styrene, or ABS materials consisting of two parts, body and lens as presented in Figure 1. The quality of the weld is ensured when the body and lens are welded together closely along the welding profile of the weld. To ensure this, the working surface profile of the block-like horn must also closely fit this profile. The width and thickness dimensions of the weld will determine the corresponding dimensions of the horn. Meanwhile, the length of the horn is determined by equation (1) [3].

$$\lambda = \frac{c}{f} = \frac{1}{f}\sqrt{\frac{E}{\rho}} = 2L \quad (1)$$

Where: c, E, ρ, L, λ, and *f* are the velocity of sound (m/sec), modulus elasticity of the horn material (Gpa), density of the horn material (kg/m^3), the horn length (mm), wavelength of mechanical vibration (μm), and longitudinal natural frequency of 20 kHz, respectively.

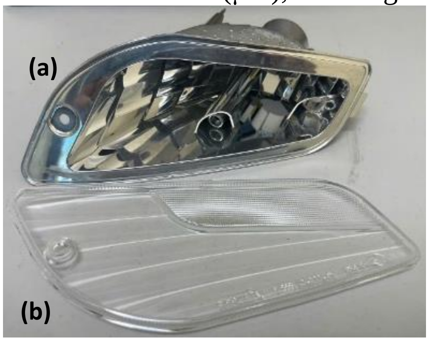

Figure 1. *Products for welding of car turn signals: (a) body, (b) lens*

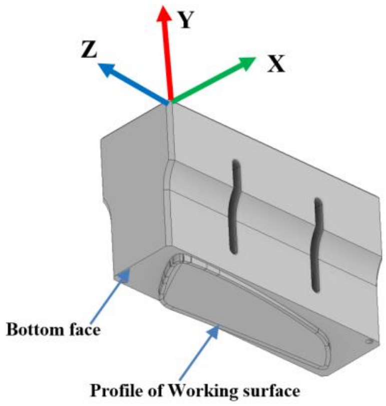

Figure 2. *A proposed 3D CAD model of a block-like horn*

There are a few types of materials that can meet the requirements for horn design in this case. According to the recommendations of previous researchers, the material is Aluminum Alloy of Al-6061-T6. This material has good acoustic properties which are shown in Table 1.

Table 1. *Properties of aluminum alloy (Al-6061-T6)*

Young' modulus (GPa)	Poisson's ratio (υ)	Density (kg/m^3)
70	0.33	2700

According to the above material parameters, the length of the horn can be obtained by calculating from equation (1), the theoretical horn value is 127 mm. According to the design recommendation [14], the horn length is selected to move within the range of ± 7% - 10% in this study. Therefore, the theoretical length of the horn is selected as 115 mm. To achieve the displacement amplitude amplification effect, it is recommended that the area of the upper surface, in contact with the booster, should be larger than the area of the lower part, where the working surface profile is located. In addition, to reduce stress concentration, the horn block should have a transition in the middle of the horn body with a sufficiently large radius R. In addition, to achieve good working efficiency, and to reduce the influence of Poisson phenomenon, slots should be introduced along the horn length. A proposed 3D design model of the horn block for this study is shown in Figure 2.

The dynamic characteristics of the ultrasonic block horn are studied by finite element method (FEM) using the commercial software ABAQUS. The FEM model meshes using a 10-node C3D10 element with a mesh size of 4 mm. This is a 4-sided quadratic element suitable for 3D design with variable cross-section and complex profile with 3 degrees of freedom at each node. The selected types of element are capable of representing different forms of damage such as creep, stress, plasticity, super elasticity, and large deformation. The accuracy of the meshing model, number of elements, boundary conditions will not be discussed in this study. The effectiveness of using this finite element analysis model can be referenced in the study [15].

In general horn analysis and design, there are two very important analysis steps to determine the dynamics properties of the horn, namely modal analysis and harmonic analysis. The first is used to determine the mode shape and the resonant frequency values of the modes. For ultrasonic welding horns, it will work effectively if the adjustment is made so that the longitudinal natural frequency appears in the resonant mode. In addition, in this analysis step, determining the frequency space, also known as frequency separation, is also very important. This criterion aims at the appearance of mode coupling between longitudinal frequency and non-longitudinal ones. The boundary condition for this analysis step is to impose control in all directions except the Y direction which is free to move. The point of applying boundary conditions is at the location of the connecting bolt between the top surface of the horn and the end of the booster as described in Figure 3 [4], [15].

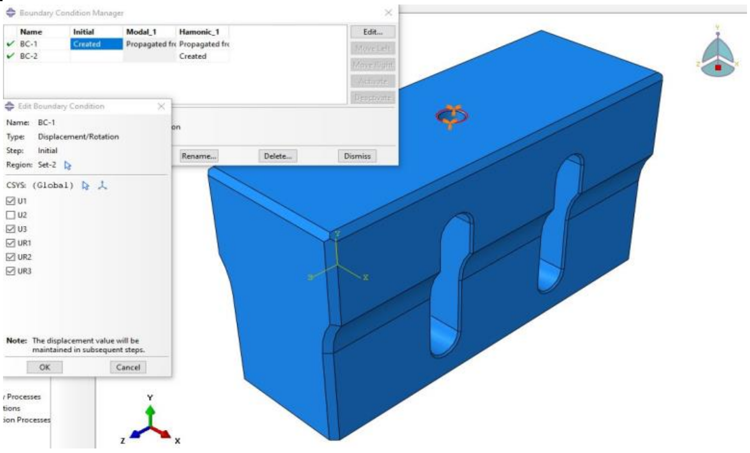

Figure 3. *Description of boundary conditions for modal analysis*

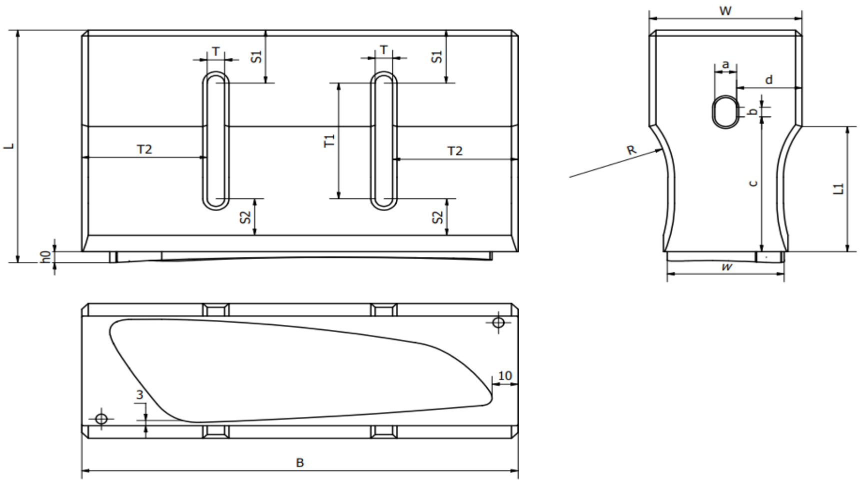

Figure 4. *Basic design dimensions of a block-like horn*

In the second step of analysis, harmonic analysis, the value of longitudinal natural frequency determined from modal analysis step is used to conduct analysis to determine the displacements inside the horn body. In particular, the displacements on the working surface profile to determine the displacement uniformity. In addition, the maximum Von-Mises stress is also determined in this analysis step. The vibration frequency amplified from the transducer-booster is the frequency of the welding machine used in this study, which is 20 kHz. This value is also called the target frequency. The boundary condition point in this analysis step is the same as the modal analysis step. However, a given displacement value is applied at this position to replace the displacement transfer from the booster to the horn. This given displacement value is 10 μm. This value is referenced from the available transducer [16]. The dimensions of the horn are shown in Figure 4. The dimensions of this modal can be seen in Table 2 with the units of millimeters. Accordingly, only the number of grooves was changed in this study. To determine displacement uniformity, 120 points located on the working surface profile were selected to extract displacement values.

Table 2. *The dimensions of the block-like horn are shown in Figure 4*

L	**L_1**	**B**	**W**	**w**	**a**	**b**	**c**	**d**	**R**	**T**	**T_1**	**T_2**	**S_1**	**S_2**
115	55	200	82	60	10	20	65	36	45	10	60	60	27.5	27.5

3. Results and discussions

3.1. The block-like horn with two slots in one direction

In this section, a block-like horn using two longitudinal grooves is used and the performance criteria of this horn will be evaluated through two analysis steps as presented above.

3.1.1. Modal analysis

Figure 5 shows the longitudinal mode shape and the pre and post ones. It is observed that the longitudinal natural frequency with the value of 20364 Hz which is different from the target frequency of 1.82%. The bending and torsion modes are the pre and post corresponding to the frequencies of 18673 Hz and 21260 Hz, respectively. In terms of frequency separation, it is observed that the first spacing between bending and longitudinal mode is 1691 Hz, while the second spacing between longitudinal and torsion modes is 896 Hz. To avoid mode coupling, the frequency isolation should be greater than 1000 Hz. The first spacing satisfies this condition, but the second one is not enough large.

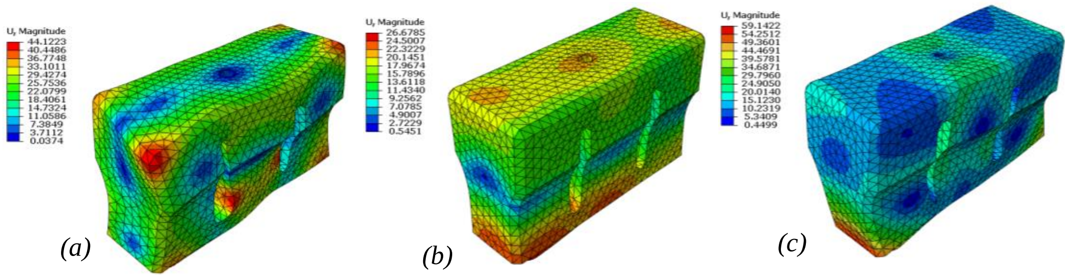

Figure 5. *Three mode shapes for the case of 2 slots along the horn length: (a) torsion, (b) longitudinal, and (c) bending*

3.1.2. Harmonic analysis

In this analysis step, the uniform displacement of the working surface profile is considered. It is seen that the color chart in Figure 6a seem more even. The displacement extracted from 120 points in working surface profile is calculated. The U value in this case is 82.3%. In addition to displacement uniformity, the maximum Von-Mises tress generated in the horn is also an important criterion to evaluate horn performance. From Figure 6b, it reveals that the maximum Von-Misses stress is around of 29 MPa. This value is smaller than fatigue strength of horn material, which is 96.5 MPa. Meanwhile, the smallest stress value is located on the working surface profile of the horn. This is beneficial because the gas in contact with the weld at high frequency, the horn will not be destroyed.

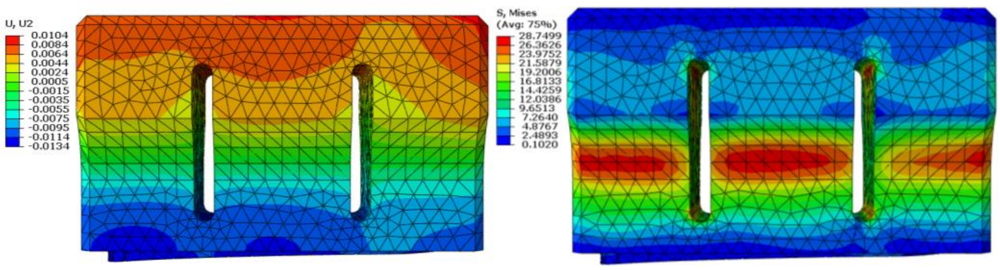

Figure 6. *Harmonic results of 2 slots along horn length: (a) displacement and (b) Von-Mises stress*

3.2. The block-like horn with three slots in one direction

The arrangement of 02 slots on one direction, as well as the combination of this option and the arrangement of one more slot on the remaining direction give a positive signal for the improvement of displacement uniformity. In this section, the number of slots on one direction will be increased to 3.

3.2.1. Modal analysis

Figure 7 shows three shape modes obtained by modal analysis. The longitudinal natural frequency in this case is 17656 kHz, which is far from target frequency by 11.7%. It can be said that this value can not match the safe frequency range which ensures efficient energy transfer and effective vibration transmission and to correctly run the welding system. The pre and post modes of the longitudinal one in this case are tortion and bending which exhibit the frequencies of 16426 kHz and 17897 kHz, respectively. The frequency separation is meaningless in this situation.

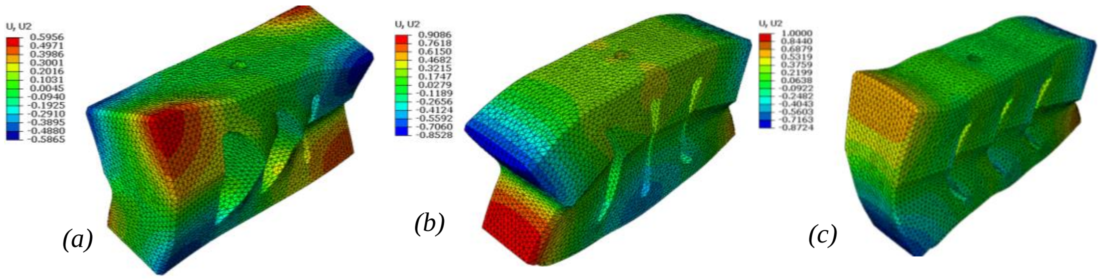

Figure 7. *Three mode shapes for the case of slots in both directions: (a) torsion, (b) longitudinal, and (c) bending*

3.2.2. Harmonic analysis

The harmonic analysis results also show that the displacement uniformity is also very small, 59%. In addition, the Von-Mises stress generated in the horn is also relatively large as shown in Figure 8. This value is 211.37 Mpa which is higher than the fatigue strength value of the horn materials. Thus, it can be concluded that for the specific application in this paper, which is welding turn signals as described in Figure 1, the use of 3 slots along the length of the horn is not reasonable.

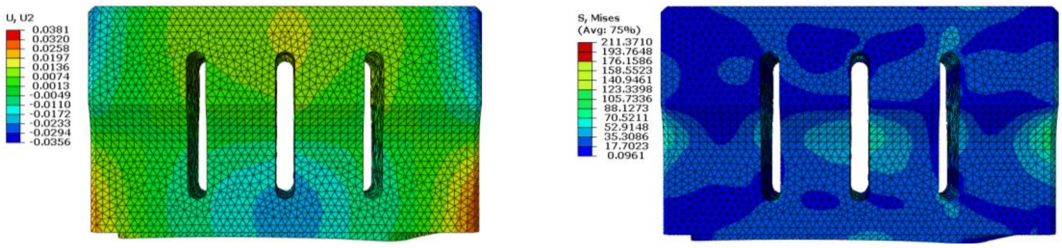

Figure 8. *Harmonic results of 3 slots along horn length: (a) displacement, and (b) Von-Mises stress*

3.3. The block-like horn with slots in 2 different directions

From the analysis results of the previous section, it can be seen that the arrangement of 02 slots along the length of the horn in one direction cannot satisfy the requirements of a design. For example, the displacement uniformity is not high, the frequency separation is not safe. Therefore, to improve the performance of the block-like horn, in this section, the slots will be arranged in both directions. In this case, the X direction is arranged with 2 slots, and one is introduced in the remain.

3.3.1. Modal analysis

Three mode shapes in this case are presented in Figure 9. It is noticed that the longitudinal natural frequency is 19665 Hz as shown in Figure 9b. This frequency value is diffrent from target one of 1.7%. The pre shape mode is bending one with natural frequency of 18733 Hz. The post shape mode is torsion one with the natural frequency of 20920 Hz. These can give the frequency separations of 932 Hz and 755 Hz. It is clear that these values can not solve the mode coupling between longitudinal and non-longitudinal modes. It is nessessary to increase these frequency spacings.

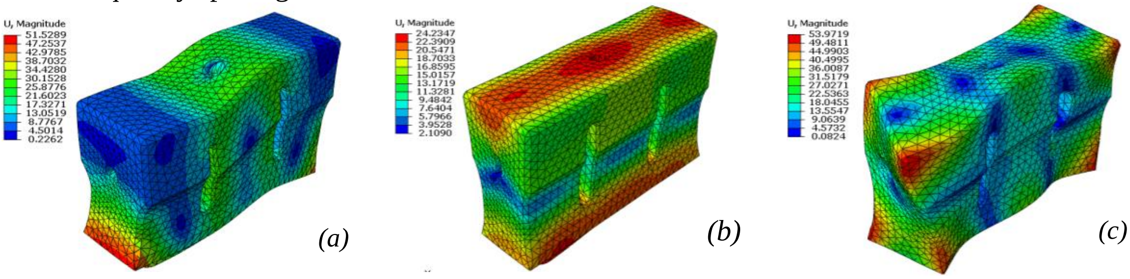

Figure 9. *Three mode shapes for the case of 2 slots along the horn length: (a) bending, (b) longitudinal, and (c) torsion*

3.3.2. Harmonic analysis

Regarding the harmonic analysis results from the Figure 10, it is observed that the colour chart shows uniformly. This refers that the displacement in the working surface profile is regular. Indeed, the U value in this case calculated is 92%. This is a relatively high value and the weld quality would be significantly improved if this simulated value could be applied to the fabrication of the block-horn after optimization.

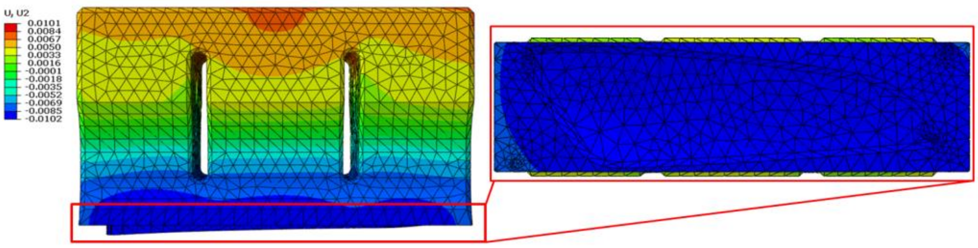

Figure 10. *Displacement in working profile in case of slots in both directions: (a) front view and (b) top view*

In terms of stress as shown in Figure 9, the results show that the maximum Von-Mises stress generated in the horn is 38.6 MPa. In fact, this value is quite small compared to the fatigue strength of the horn material. Thus, it can be seen that the arrangement of slots on both directions significantly improves displacement uniformity in the working surface profile. For a complex working profile, which is a curved profile in space as in this design, the value of 92% of U is a positive approach to be able to explore more options to increase displacement uniformity.

4. Conclusions

This paper analyzes the effect of the number of slots created on the block-like horn on the design criteria of the horn used in ultrasonic welding of plastics. The block-like horn in this study is a type of complex working profile horn used in turn signal welding made of ABS materials. Two analyses were used, namely modal analysis and harmonic analysis, using the finite element method. Preliminary results about the effect of slot numbers on the block-like horn performance were detected. Some conclusions can be drawn as follows:

- To create the highest working efficiency of the ultrasonic plastic welding system, it is necessary to adjust the design parameters so that the longitudinal mode which is in resonance state appears.

- The number of slots, as well as the arrangement of slots on the directions have a great influence on the required performance of a block-like horn. The results show that with block-like horns, slots should be arranged on both the thickness and width directions of the horn. The arrangement of slots will create space so that when the horn resonates in the axial direction, it will cause the material to deform in the lateral directions, and there will be space to accommodate this deformation. If there is no space created by the slots, the material will deform and squeeze each other, causing the phenomenon of uneven displacement on the working surface profile.

- From the results of the three case studies, it can be seen that each case has its own advantages in terms of design criteria. However, no case can ensure that all design criteria are met. It can be concluded that these are only initial preliminary results, it is necessary to continue researching the optimization of the structure of block-like horn in a larger range with more input variables. This study lays the foundation for developing methods for optimal design of horns used in the field of ultrasonic welding of plastics with complex curved profiles.

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