A novel single-element transducer with curved surface for cavitation detection

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Abstract. Acoustic cavitation is increasingly used to apply in industrial and clinical areas. However, with the development of these fields, the precision of devices used to monitor cavitation activity gradually cannot meet the needs of the higher accuracy requirements of practical application. In this paper, we propose several design schemes of a novel passive cavitation detector (PCD) which is hoped to have better measuring performance than traditional plane PCD because of its focusing effect. By conducting FEM simulations, the optimal design plan and the surface curvature of PCD were chosen. It is shown that the measuring ability of the final selected PCD is near 1.7 times of traditional plane PCD.

1. Introduction

Recently, ultrasonic cavitation has received increasing attention since its non-invasive cleaning performance and many potential chemical properties, which are expected to present new opportunities for ultrasonic cleaning as well as therapy [1]. Ultrasonic cavitation is a phenomenon caused by the interaction between ultrasonic waves and liquids [2]. Based on the condition and lifecycle of micro-bubbles generated by cavitation, ultrasonic cavitation activities are normally classified into two classes: stable cavitation and inertial cavitation [3], which has been proven to be the key point of the application of cavitation activities. The application effects of different cavitation activities vary significantly, and serious consequences, such as tissue destruction when drug delivery process under cavitation [4] could be resulted if the cavitation activity is misused. Thus, it is crucial to distinguish these two conditions and leave the applied cavitation activity in a correct state.

A passive cavitation detector (PCD) is one of the most common devices for measuring the acoustic information caused by cavitation [5] due to its cost-effective technology. By transforming the received acoustic information that emitted by cavitation activities into electric signals, a PCD can achieve a real-time detection of cavitation activities [5]. Although PCDs have been widely used, its monitoring performance is still not accuracy enough, especially in fields that have high precision requirements like clinical medicine [4]. Moreover, nowadays, most of the improvements of PCD are concerned with the optimization of manufacturing materials of PCDs, while there are few studies focus on the construction modification of PCDs [6]. Therefore, the development of a novel PCD construction would represent a breakthrough for improving the detecting performance of traditional PCDs.

In this paper, to improve the detection ability, a novel curved PCD was proposed. Compared to traditional PCD with plane detecting surface, this novel PCD has almost 1.7 times sensitivity to the...
magnitude of acoustic waves in the focusing area. This means that the novel PCD can contribute to a higher monitoring accuracy and satisfy the high-precision clinical demands.

2. Modeling and Methods
To achieve a higher-level measuring precision, two main improvement plans of PCD construction modification were put forward. In this section, PCD with double curved layers and PCD with a single curving surface were compared in detail, and relative finite element method (FEM) models had been established to compare the detecting performance of these two designed PCDs.

2.1. Design plans
The basic design concept of both two design plans is increasing the detection accuracy by modifying the grade of the PCD surface curvature. It is known that the curving surface would have a better focusing effect and then bring higher monitoring performance compared with the plane detecting surface. A traditional PCD consists of the matching layer, the piezoelectric layer, and the backing layer. To implement the expected curving detecting surface, the structures of PCD layers should be reshaped, which has mainly two schemes as follow:

![Figure 1: The schemes of two curving surface PCDs. (a) PCD with two curving layers. (b) PCD with a single curving layer.](image)

The overall FEM schemes of two designed PCDs are illustrated in Fig. 1. The first design plan is PCD with double curving layers, and the second is with a single curving layer. Although the more curving layers mean the longer manufacturing period, the first plan that has two curved layers satisfies the consistency of the thickness of the matching layer, while the plan is shown in Fig. 1 (b) has various thicknesses of its matching layer. For PCD with a single curving layer, based on the optimal matching layer thickness of 2mm (a quarter of wavelength), there are two further design plans, as shown in Fig. 2. In the first scheme, the ideal thickness of 2mm is located at the center of the PCD surface. In the second plan, the ideal thickness is located at the middle of the PCD surface radius.

![Figure 2: The schemes of the designed PCDs with the ideal thickness of 2mm of matching layer is located at different locations.](image)
2.2. *FEM simulation*

The FEM simulation was conducted in Onscale (Redwood City, California, USA). The FEM model of designed PCDs was established and the detailed material information is given in Table 1. To simulate the stable cavitation activity, the sinusoidal wave with 500kHz center frequency and 50 μs running time was emitted from the center of the piezoelectric surface and detected by the measuring point located at 30mm away from the PCD surface. After comparing the measuring performances of these three PCD design plans, the best scheme was chosen, and its surface curvature was adjusted several times to find out the optimal detecting surface curvature.

| Layer                | Material          | Density (kgm⁻³) |
|----------------------|-------------------|-----------------|
| Matching layer       | Vantico           | 1149            |
|                      | HY1300/CY1301     |                 |
| Piezoelectric layer  | Polyvinylidene    | 1780            |
|                      | fluoride          |                 |
| Backing layer        | 20% VF            | 4800            |
|                      | tungsten/epoxy    |                 |

### Table 1: Material of PCDs.

#### 3. Results and Discussion

The acoustic wave forms generated from the FEM simulation are described in Fig. 3. And the relative acoustic information is shown in Table 2. According to the acoustic pressure figure, PCD with double curving layers has the highest peak pressure amplitude. Besides, it is PCD with double curving layers that possesses the highest rise time (RT) and full-width-half-maximum (FWHM) among three design plans. Therefore, PCD with curving matching and piezoelectric layers can contribute to a better detecting performance and will be applied to the following experiments. This means that in the first plan, all signals would go through the same distance in the matching layer, which has a more stable measuring result. But in the second plan, signals received from the different surface points would experience various matching layer thickness, and the results are likely to be affected.

![Normalized acoustic pressure](image)

Figure 3: The normalized acoustic pressure of different designed PCDs in FEM simulation period.

#### Table 2: Acoustic information from FEM simulations.

| PCD                                                      | RT [ns] | FWHM [ns] |
|----------------------------------------------------------|---------|-----------|
| PCD with double curving layers                           | 424.98  | 651.30    |
| Single curving layer PCD, 2mm located at the center of surface | 386.13  | 591.29    |
| Single curving layer PCD, 2mm located at the middle of surface radius | 373.90  | 634.49    |
Based on the optimal designed PCD, the measuring performances of this PCD with different curvatures are compared. Table 3 shows that PCD with 20mm is provided with the supreme RT, FWHM and peak positive pressure amplitude (PPPA). Thus, 20mm is the optimal surface curvature of the chosen PCD, then compared it with the traditional PCD with plane monitoring surface. The maximum pressure fields of these two PCDs are illustrated in Fig. 4. The maximum acoustic pressure of curving and plane PCDs are 7.03e+01 dB and 4.13e+01 respectively, which means that the monitoring performance of the designed curving PCD is about 1.7 times to PCD with plane surface.

Table 3: acoustic information of PCD with different curvature radii.

| PCD  | RT (ns) | FWHM (ns) | Normalized PPPA (+) |
|------|---------|-----------|---------------------|
| R=20mm| 326.01  | 613.93    | 57.36               |
| R=30mm| 330.45  | 634.69    | 40.90               |
| R=40mm| 373.59  | 655.416   | 34.76               |

4. Conclusion
In this paper, we have shown that different design schemes of curving PCDs are expected to have better measuring performance for cavitation activity. These design plans were compared through FEM simulation and the optimal scheme was chosen to be used in the following experiments. The traditional plane PCD, by contrast, its monitoring ability is far inferior to the designed PCD with a curving surface. Altogether, the detecting performance of selected PCD is 1.7 times the traditional one, which is hoped to meet the high precision requirements of fields like medicine.

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