A new radiation force balance for acoustic power measurement of ultrasonic phased array

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Abstract: The ultrasonic phased array has been used for research and application of focused ultrasonic treatment for at least 20 years. However, due to the complexity of its working modes, there is still lack of simple convenient and effective method to measure the acoustic power transmitted by the phased array. In this paper, a new radiation force balance (RFB) method based on a absorbing target of convex spherical segment is proposed for measuring the output acoustic power of the array. The measurement principle, system and procedures of this method are described, and the ratio $r = P/cF$ for various combinations of array elements is derived, where c is speed of sound in water, P is the output acoustic power and F is the axial radiation force acting on the target, which provides a basis of designing and applying the measurement system.

Key words: radiation force balance (RFB); phased array; spherical segment; absorbing target

0 Introduction

It is known that the radiation force balance (RFB) method is the preferred method for acoustic power measurement[1-2]. However, due to changeable operating setting and acoustic beam orientation, the existing RFB is not suitable for multi-mode acoustic power measurements of the ultrasonic phased array. In this paper, a new RFB method based on a convex absorbing target is proposed to achieve this measurement.

1 Principle

Ultrasonic phased array incorporates dozens or even hundreds of small planar piston transducer elements, which are generally installed on the inner surface of a large spherical segment. During the operation, the phases, sometimes with the amplitudes together, of the driving voltages applied to array elements are controlled to obtain various required acoustic focusing characteristics (including multi-beam) of the array, for which, the performances of all array elements are required to be independent of each other theoretically. Therefore, in the design of the ultrasonic phased array, some technical measures in the acoustic structure and manufacturing process need to be taken to minimize the interaction between elements.

Fig.1 is the schematic diagram of the ultrasonic phased transducer array with a absorbing target of convex spherical segment. The radius of the transmitting surface of each array element is a; the radius of the inner tangent sphere (i.e. the transmitting surface) of the phased array, which is composed of the transmitting surfaces of all array elements, is R. The radius of the convex spherical segment absorbing target is $(R-d)$, and its sphere center is just the sphere center of the phased array, where $d<a^2/\lambda$ and a^2/λ is the distance of the near field (transition region), λ is the wavelength of sound in water. Since the absorbing target is always in the near field of each array element, the transmitting sound wave of each transducer is approximately a plane wave and isolated from each other. Thus, the transmitting acoustic power of the ith transducer is $P_i = cF_{ni}$, where F_{ni} is the normal radiation force of the ith transducer acting on the absorbing target and c is the sound speed in water. Assuming that the angle between F_{ni} and the acoustic beam axis of the phased array (i.e. the direction of measuring unidirectional force) is α_i, which is the design parameter of the array, then the $F_i = F_{ni}\cos\alpha_i = P_i\cos\alpha_i/c$ is the projection of F_{ni} on the acoustic beam axis of the phased array, where i = 1,2,3,...N is the sequence number of array elements, and the ultrasonic phased array has a total of N elements.

Thus, the transmitting acoustic power of the i th

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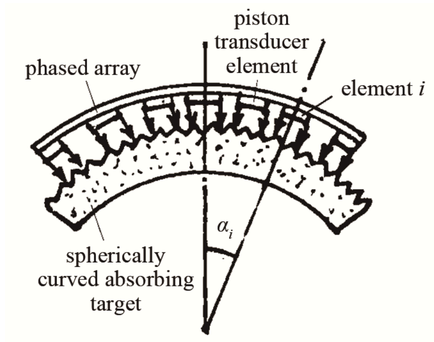
transducer is

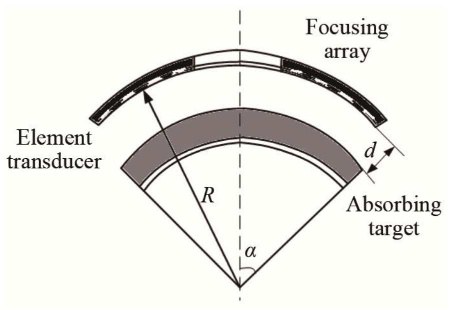
$$P_i = \frac{cF_i}{\cos\alpha_i} \tag{1}$$

When n array elements ($n \leqslant N$) are combined to transmit acoustic power at the same time, the apparent total acoustic power is

$$P_{\text{app}} = \sum_{i=1}^{n} P_i = c\sum_{i=1}^{n} \frac{F_i}{\cos\alpha_i} \tag{2}$$



(a) Basic structure



(b) Geometric representation

Fig.1 Schematic diagram of ultrasonic phased array and convex spherical absorbing target

The axial radiation force F_i of each element transducer acting on the absorbing target is measured respectively, and the corresponding output power P_i is calculated by Formula (1). Then the apparent total acoustic power of various element combinations can be calculated by Formula (2). But, this is not the real total acoustic power transmitted by the element combination due to the fact that the interaction between array elements cannot be ignored when the array elements are transmitting simultaneously, especially when the transmitting acoustic power is very great. Therefore, it is required to assume that the mutual influence between elements for each element is equal when the array elements are combined to transmit acoustic power at the same time. In other words, the proportional relationship $q_i = P_i / P_0$ is constant in the case that each element transmits acoustic power alone or transmits with other elements together, where i = 1,2,3,...N and P_0 is an arbitrary reference acoustic power. Consequently, the real total acoustic power transmitted by the combination of n elements is $P = \Sigma P_i = P_0 \Sigma q_i$ and i =1 to n.

Moreover, when the n elements simultaneously transmit acoustic power, the total axial radiation force F acting on the absorbing target is equal to

$$F = \left(\frac{P_0}{c}\right) \sum_{i=1}^{n} q_i \cos\alpha_i \tag{3}$$

For different element combination, the ratio $r = P/cF$ is defined by

$$r = \frac{P}{cF} = \frac{\sum_{i=1}^{n} q_i}{\sum_{i=1}^{n} q_i \cos\alpha_i} \tag{4}$$

Thus, the total acoustic power transmitted by the phased array with the combination of n elements can be determined from the measured total axial radiation force as follows:

$$P = \frac{\sum_{i=1}^{n} q_i}{\sum_{i=1}^{n} q_i \cos\alpha_i} cF \tag{5}$$

2 Measurement system and procedure

Fig.2 is a schematic diagram of the measurement system. The geometric relationship between a phased array and a convex absorbing target remains as shown in Fig.1. The absorbing target is suspended by three nylon wires, and the upper ends of the nylon wires are evenly distributed on a ring-shaped frame above the tank. In order to increase the inertial mass of the main balance system, restrain the transient response of the balance and improve the stability and repeatability of the force reading, the counterweight 1 is added in the degassed water under the absorbing target. On the outer circumference of the ring-shaped frame, a long handle located at the same plane of the frame is installed, and the extension line of the central axis of the handle passes through the center of the ring-shaped frame. The long handle and a supporting wedge (as a fulcrum) form a lever system. On the right-hand end of the lever there is a counterweight 2 to balance the sinking force of the target plus the counterweight 1. A

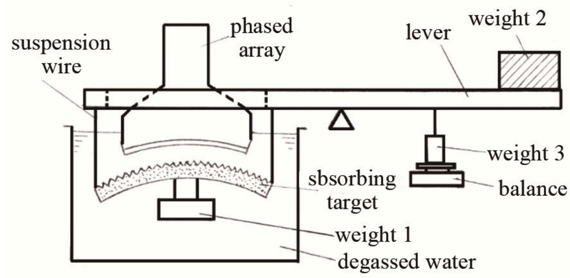


Fig.2 A RFB system for measuring the acoustic power transmitted by ultrasonic phased array

counterweight 3 is suspended at a proper position on the right of the fulcrum, and its weight is adjusted to make its downward force close to the middle value of the measurement range of the electronic balance.

The measurement procedure is as follows:

Firstly, the acoustic power P_i transmitted by each element transducer needs to be measured. By using the RFB system the corresponding axial radiation force F_i is measured, and by using the known tilt angle α_i, the N independent acoustic power P_i values and the corresponding q_i values can be obtained by Formula (1).

Then, the transmitting combination of n elements ($n \leqslant N$) is formed according to the measurement purpose, and the total axial radiant force F is measured by the RFB system when all the n element transducers transmit acoustic power simultaneously. Formula (5) can be used to obtain the total acoustic power P transmitted by the phased array with a given element combination.

3 Conclusion and discussion

This paper proposes a new RFB method for measuring the output acoustic power of ultrasonic phased transducer array. The innovation lies in the use of a special absorbing target of convex spherical segment to measure the near-field radiation force of each element transducer. The transmitting acoustic field of each element can remain independent even when the acoustic power is transmitted by the combination of some array elements or the whole array. Thus, the difficult problems in the measurement of radiation force, such as the interference effect between element acoustic beams and the synthetic beam deflection effect caused by phase control, are avoided. The basis of the measurement is separately to measure the acoustic power of each element transducer when it transmits alone, and then add them together to obtain the apparent total acoustic power P_{app}. When the array elements are combined to transmit simultaneously, the real total acoustic power P is calculated by the Formula (5) associated with the total axial radiant force F measured under the actual transmitting condition. The premise of this calculation is to assume that the proportional relationship of the transmitting power for each element of the array is the same as that when the element transmits alone. The reasonability and feasibility of this assumption depends on the design and manufacturing technology of the transducer array, that is mainly the degree of acoustic isolation and electrical shielding between array elements. Therefore, it is an uncertain factor. How to measure the parameters of acoustic isolation and electrical shielding between array elements before measurement for uncertainty assessment needs to be further studied. Due to the relatively small target distance d, the effect of reflection wave from the target should also be considered, including the influence of reflection wave on the working state of transmitting transducer.

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辐射力天平法测量相控阵超声换能器的声功率

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摘要：超声换能器相控阵已用于聚焦超声治疗的研究和应用已有 20 多年历史，但其声功率 P 的测量仍缺乏方便有效简易的测量方法。文章旨在提出一种基于凸球面吸收靶的辐射力天平(Radiation Force Balance, RFB)方法，测量其声功率。理论推导了这种 RFB 在各种阵元组合下的比值 $r = P/cF$ (c 为水中声速，F 为阵的声束轴方向的总辐射力)。论述了测量各种组合的发射声功率的实施方法和测量程序。为实际的测量系统设计和应用建立了良好的工作基础。

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