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Acoustic power measurement of high intensity focused ultrasound in medicine based on radiation force ☆

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Abstract

How to measure the acoustic power of HIFU is one of the most important tasks in its medical application. In the paper a whole series of formula for calculating the radiation force related to the acoustic power radiated by a single element focusing transducer and by the focusing transducer array were given. Various system of radiation force balance (RFB) to measure the acoustic power of HIFU in medicine were designed and applied in China. In high power experiments, the dependence of radiation force acting the absorbing target on the target position at the beam axis of focusing transducer was fined. There is a peak value of "radiation force" acting the absorbing target in the focal region when the acoustic power through the focal plane exceeds some threshold. In order to avoid this big measurement error caused by the 'peak effect' in focal region, the distance between the absorbing target of RFB and the focusing transducer or transducer array was defined to be equal to or less than 0.7 times of the focal length in the National Standard of China for the measurements of acoustic power and field characteristics of HIFU. More than six different therapeutic equipments of HIFU have been examined by RFB for measuring the acoustic power since 1998. These results show that RFB with the absorbing target is valid in the acoustic power range up to 500 W with good linearity for the drive voltage squared of focusing transducer or array. The uncertainty of measurement is within ±15%.

Keywords: HIFU; Acoustic power; Measurement; Radiation force

1. Introduction

The radiation force balance (RFB) was developed to measure the plane wave acoustic power more than 60 years ago. K. Beissner [1] derived the radiation force expression for an absorbing target in focused ultrasound field. However the acoustic power measurement of HIFU field using RFB has not been studied in all details. This paper expressed some researches in the field in Shanghai JiaoTong University, the Institute of Hai Ying Electronic Medical System Co., Ltd. and the Institute of Ultrasound Engineering in Medicine of Chongqing University of Medical Sciences since 1997.

2. Theory

2.1. The radiation force acting on a cone-shape target in the field of single focusing transducer

Based on ray acoustics and superposition theorem, the general relation between the axial radiation force F acting on a partially reflecting (or partially absorbing) target with a cone-shape and the acoustic power P of a spherical zone

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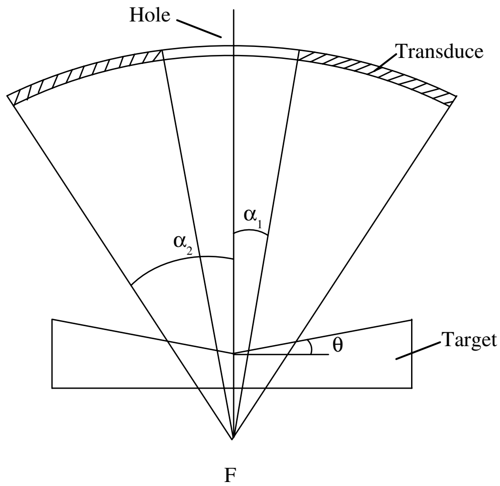

Fig. 1. The geometrics of the spherical zone focusing transducer and the cone-shape target.

transducer, a spherical bowl with a circular centre hole, was derived [2] when the position of the target is between the focusing transducer and its focus (Fig. 1) as following:

$$F = P[(1 + r^2 \cos 2\theta)(\cos 2\alpha_1 - \cos 2\alpha_2) + r^2 \sin 2\theta(2\alpha_1 - \sin 2\alpha_1 - 2\alpha_2 + \sin 2\alpha_2)] \times [4c(\cos\alpha_1 - \cos\alpha_2)]^{-1} \quad (1)$$

Here, ρ is the pressure amplitude reflect coefficient of the target in water and c is the speed of sound in medium (water). α_1 is half of the internal hole aperture angle of the spherical zone transducer and α_2 is half of the outer aperture angle of the spherical zone transducer. θ is the dip angle of the taper-shape target, and θ is positive for the concave taper, and negative for convex taper.

For the plane piston transducer ($\alpha_1 = \alpha_2 = 0$), the acoustic power can be calculated by

$$P = FC/(1 + r^2 \cos 2\theta) \quad (2)$$

For a total reflecting target ($r = 1$) and a holed focusing transducer

$$P = 4Fc(\cos\alpha_1 - \cos\alpha_2)/[(1 + \cos 2\theta)(\cos 2\alpha_1 - \cos 2\alpha_2) + (2\alpha_1 - \sin 2\alpha_1 - 2\alpha_2 + \sin 2\alpha_2)\sin 2\theta] \quad (3)$$

For a total reflecting target ($r = 1$) and a spherical segment (bowl) focusing transducer ($\alpha_1 = 0$)

$$P = Fc(1 - \cos\alpha_2)/[\cos^2\theta \sin^2\alpha_2 + (\sin\alpha_2 \cos\alpha_2 - \alpha_2) \sin\theta\cos\theta] \quad (4)$$

For a total reflecting target ($r = 1$) and a plane piston transducer ($\alpha_1 = \alpha_2 = 0$)

$$P = Fc/2\cos^2\theta \quad (5)$$

For a total absorbing target (r=0) and a holed focusing transducer

$$P = 2Fc/(\cos\alpha_1 + \cos\alpha_2) \quad (6)$$

For a total absorbing target ($r = 0$) and a spherical segment (bowl) focusing transducer ($\alpha_1 = 0$)

$$P = 2Fc/(1 + \cos\alpha_2) \quad (7)$$

For a total absorbing target ($r = 0$) or the reflecting target with convex taper angle of 45° and a plane piston transducer ($\alpha_1 = \alpha_2 = 0$):

$$P = Fc \quad (8)$$

Formulas (2),(5),(7),(8) are well-known, and formula (1),(3),(4),(6) were derived in 1998. They are very useful in practice.

2.2. The radiation force acting on a total absorbing target in the field of a focusing transducer array

The focusing transducer array is composed of identical transducer elements symmetrically distributed on a spherical surface, either plane pistons or spherical concave bowls as shown in Fig. 2 when the main acoustic axis of the array is perpendicular to the total absorbing target. The beam of every transducer element has its individual incident angle. If every element of the array is the same piston-shape transducer with identical acoustic power, and the number of element is N, the incident angle of the ith element θ_i is, according to R.C. Preston's method [3], the total acoustic power P of the array can be calculated by

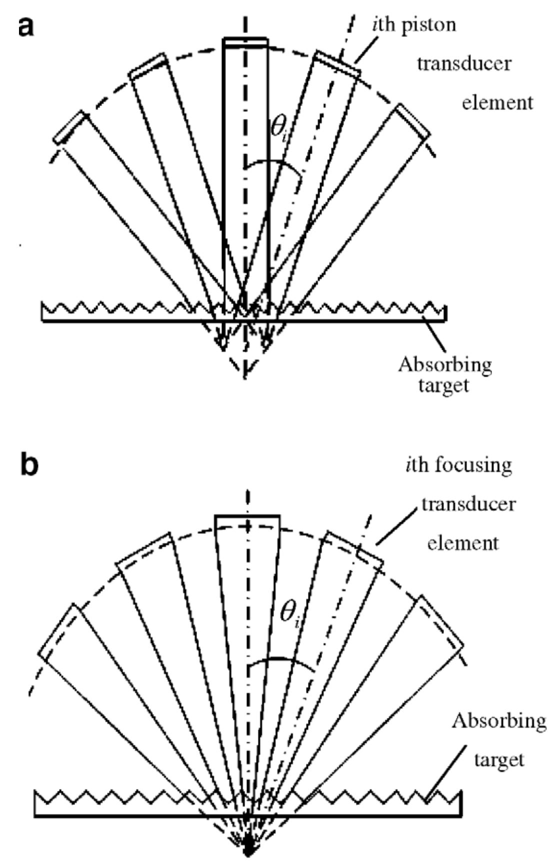

Fig. 2. Focusing arrays with different transducer elements: (a) with piston transducer elements, (b) with focusing transducer elements.