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Design of ultrasonic wedge transducer ☆

Guillermo Rus [a,b], Shi-Chang Wooh [a,*], Rafael Gallego [b]

[a] NDE Lab, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Room 1-272, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
[b] Department of Structural Mechanics, University of Granada, Politécnico de Fuentenueva, 18071 Granada, Spain

Abstract

Cones and wedges inserted between an ultrasonic transducer and the specimen provide the transducer (circular or rectangular shape) with enhanced capability for point or line contact with the specimen. Such an arrangement is useful in that the transducer can be used for transmitting to and receiving from a point (or line) source, and that it can eliminate the undesirable aperture effect that makes the transducer blind to waves traveling in certain directions and those of certain frequencies.

In this paper, a comprehensive numerical analysis based on a wave propagation model is carried out for the study of characteristics and parameters of cones and wedges influencing their performance. We study the effect of the dimensions, shape and aperture on the frequency response and the angle of incidence of the wave. For computational accuracy and efficiency, the boundary element method is used in the analysis.

Keywords: Point source; Point transducer; Conical transducer; Boundary element method (BEM)

1. Introduction

Ultrasonic transducers used in nondestructive evaluation (NDE) and testing (NDT) are traditionally made in circular or rectangular shapes of finite dimensions (typically 0.5–2.5 cm diameter). Although these transducers are easy to fabricate and they provide strong and well-directed signals, there are some disadvantages associated with their relatively large dimensions with respect to the wavelengths. The main disadvantages to a large transducer include signal distortion, cutting-off of certain frequency components, and the near field effect, which are referred to as the *aperture effects* in general.

The benefits of using point sources and point receivers to NDE have been addressed by Sachse [4]. One of the ways to produce point contact between the transducer and the target surface is to use a miniature or pencil-tip transducer. The use of wedges to collimate waves and to generate point sources has been first introduced by Ying in 1967 [9].

The propagation of ultrasonic waves radiated from a transducer was studied by many investigators in an effort to understand the response of the transducer as a system. Kimoto and Hirose [2] studied a transmitter–receiver setup by modeling the transmitting transducer as a distributed traction and using a weight function on the displacements of the receiving transducer. To improve the model of the transducer, Schmerr [5] introduced the transfer function for the transducer–specimen system. Wooh and Zhou [7,8] and Shi and co-worker [6] studied the behavior of laser excited ultrasonic bulk and guided waves, respectively.

Despite the abundance of such studies and the fact that the wedges have been used in practice for long time,

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* Corresponding author. Tel.: +1 617 253 7134/6044; fax: +1 617 253 6044.

E-mail address: scwooh@mit.edu (S.-C. Wooh).

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the response of the wedge has not been studied in great detail. We report the results of a comprehensive parametric study in an effort to establish a guideline and criteria for an optimum wedge design. The conclusions drawn from our numerical study allow us to predict the influences of boundary conditions and wedge geometries on the transducer–specimen coupling mechanisms.

2. The transducer design aspects

As an example to realize the aforementioned aperture effects, we consider a large transducer used in detecting Rayleigh surface waves. The response of the transducer can be expressed by the superposition of the wave displacements detected by the transducer as the wave propagates through the surface of contact between the transducer and the target material. The aperture effect consists of vanishing signals due to the cancellation of the waves when the contact area is coincident with the wavelength.

This problem of the vanishing frequency components can be resolved by physically reducing the size of contact area using a wedge.

3. System response

3.1. Linear time-shift invariant

The complete NDE system can be decomposed as a sequence of elements, each of which can be assumed linear time-shift invariant. The objective here is to analyze the performance of the wedge working as a participating component of a complete measurement system. Because of this linear decomposition, each of the linear transfer functions of both wedges remain invariant through a test in regard to the wedge design, it is only necessary to study these response variations for different wedges.

A wedge can be used either as a transmitter or receiver, or both at the same time. For this, it is arguably sufficient that we only need to study the frequency response of transducers located at two well-chosen points.

3.2. Models and reciprocity

The transmitting wedge–specimen system model is shown in Fig. 1(a), in which the piezoelectric transducer is simply modeled as pressure distributed uniformly on the contact area Γ_c. Using this model, we can compute the particle displacements in the radial direction (**n**) at all the points *z* located on an arbitrary arc of fixed radius *r*. This allows us to study the directional dependency or the *directivity* of the waves propagating into the medium. To study the characteristics of the receiver assembly, a reciprocal model shown in Fig. 1(b) is considered. In this model, the particles on the arc of radius *r* are loaded in the **n**-direction by applied pressure in the form of Dirac delta function. Then, the output signal is calculated by integrating the normal displacements over the surface (Γ_c) of the contact between the wedge and the receiving transducer.

It is sufficient to study only one of these models in order to analyze both cases, because the reciprocal model can be proven to produce identical results.

3.3. Boundary element method

In studying and designing the wedge–specimen systems, we use the boundary element method (BEM) because of its clear advantages over the finite element or other discrete methods. First, the BEM does not require re-meshing of the body domain at each iteration. This not only reduces the computational time but also eliminates small but important perturbations due to the changes of the mesh. Second, by reducing the dimension of the problem by one, the fine meshes required by high frequency become affordable through the BEM.

In implementation, we assume that the wedge–specimen interface is in perfect contact and the specimen is modeled in the linear regime. Also assumed is that the transducer face is loaded by a uniformly distributed stress field varying in time, which prescribes the boundary condition. We use the classical conforming discreti-

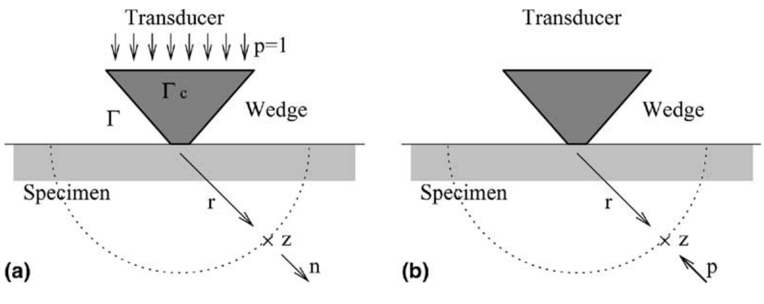

Fig. 1. Definitions of two reciprocal problems: (a) transmitter and (b) receiver.

zation scheme with quadratic elements, 8-point Gauss integration after regularization and displaced collocation strategy. The so-called singular boundary integral equation is used for both boundary and internal points [1,3]. The model was discretized with approximately 70 quadratic elements and with a frequency sampling between 0 and 1 MHz at an increment of 10 kHz. The material used in this study is 4340 steel. The parametric design is based on the model shown in Fig. 2. It shows the transmission of energy into the specimen through a wedge. This model is used to compute the transfer function of the combined assembly and directivity analysis.

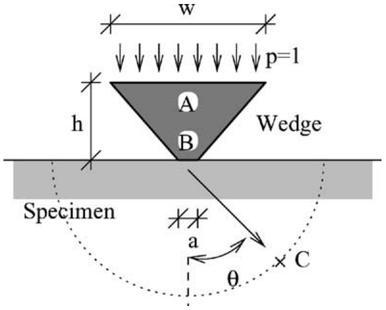

Fig. 2. Model used in the wedge design.

4. Numerical results

For the sake of convenience and without losing generality for conclusions, we only consider two-dimensional problems, in that a wedge is assumed to have infinitely large dimension in its lateral direction. From the practical point of view, we use a fixed value of 2.54 cm (1.0 in.) for the dimension *w* (area of contact between the transducer and the wedge). In Figs. 3–6 the height *h*, the base contact area *a* with the specimen and the shape are varied and commented to study their influences on the transfer function.

5. Conclusions

A few simple but important guidelines for the design are obtained:

- A small contact area improves the directivity.
- Medium height is best, since higher interfaces have an uniform response in terms of directivity and frequency, but too much slenderness attenuates excessively high frequencies.
- Horn-like shapes do not necessarily improve the performance.

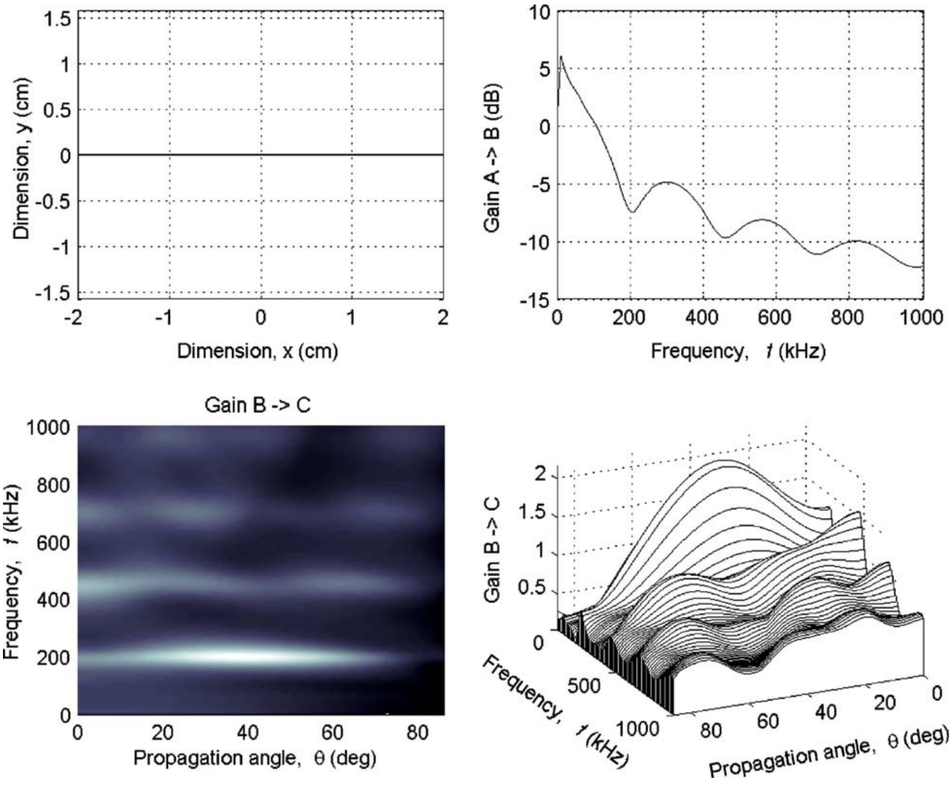

Fig. 3. Design 0 (no wedge). Combined frequency and directivity. Above left: cross-sectional view of the wedge. Above right: frequency-dependent gain produced by the wedge itself (from transducer *A* to specimen contact *B*). Below: two perspectives of the frequency-directivity gain from point *B* to the arc *C* (internal point in the specimen at every angle). Both gains should ideally be as horizontal and uniform as possible. Direct transducer–specimen contact gives undesirably wavy response in both frequency and directivity.

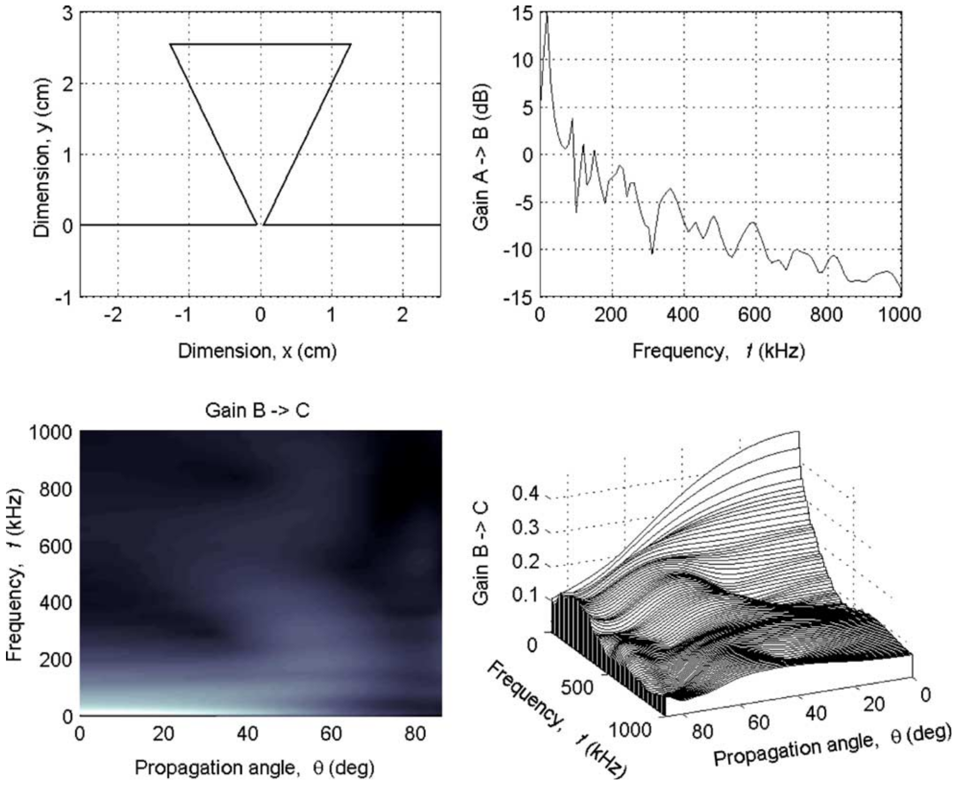

Fig. 4. Design 1. A taller linear wedge with medium contact area provides improved response in both directivity and frequency.

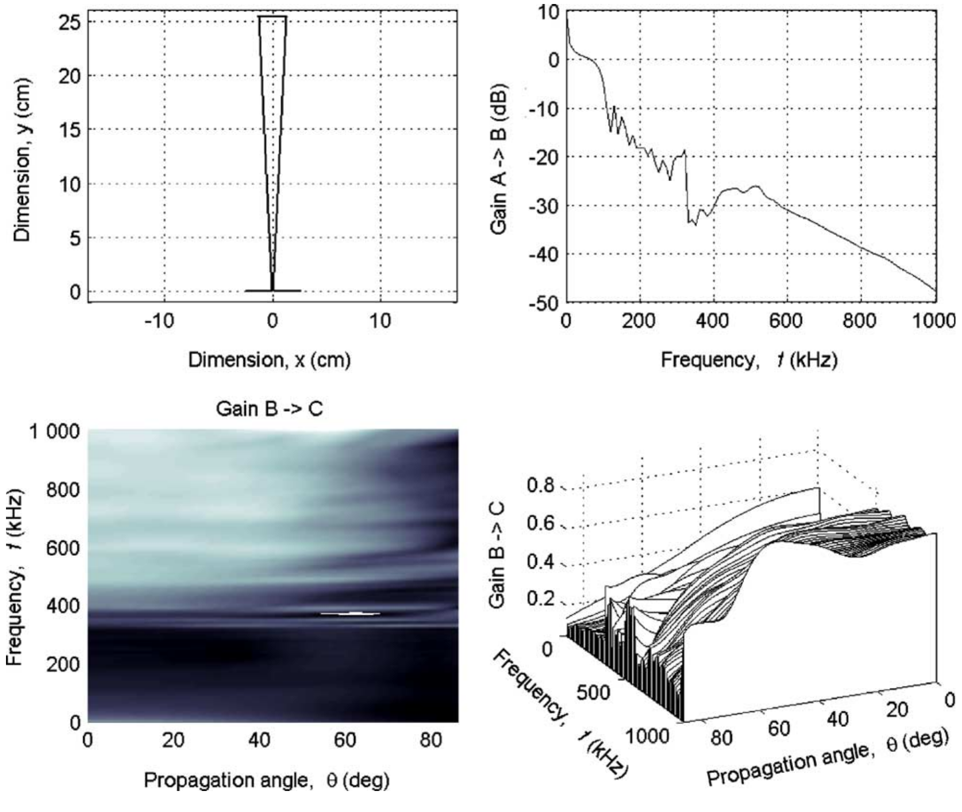

Fig. 5. Design 2. An extremely tall wedge provokes instabilities due to excessive attenuation (−40 dB $A - B$) at high frequencies.

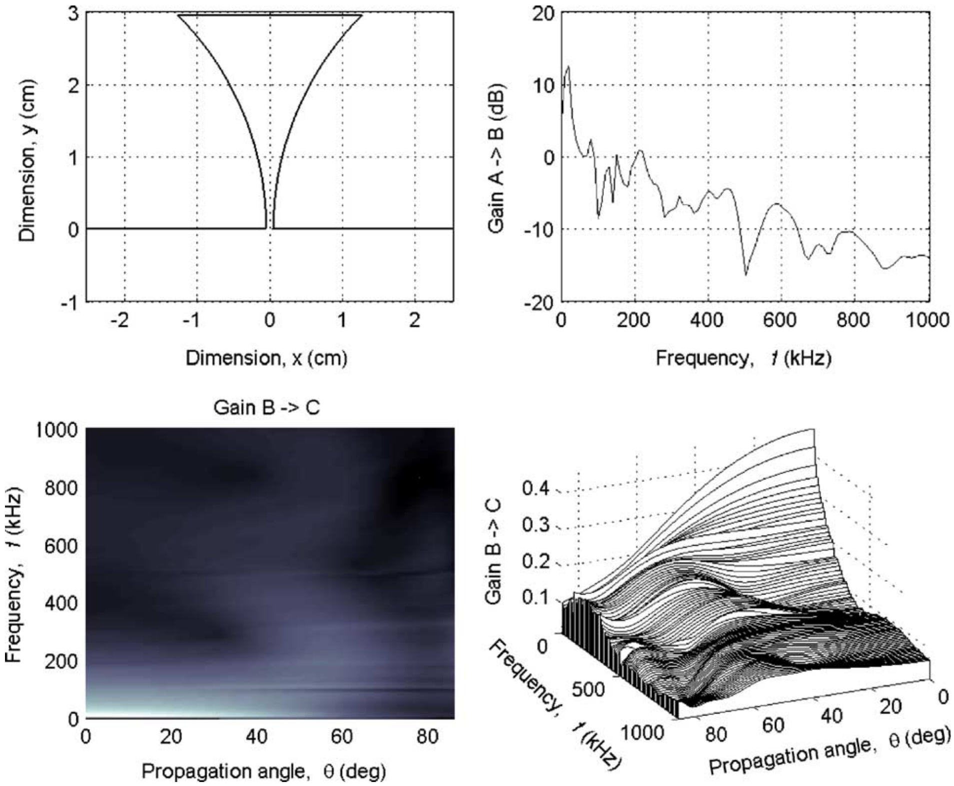

Fig. 6. Design 3. The frequency and directivity responses of a horn-like wedge are similar to those of Design 5, but it provides a worse gain $A - B$.

- The response is significantly improved for all frequencies in the spectrum.

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