Design of ultrasonic wedge transducer

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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.

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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,
the response of the wedge has not been studied in great
detail. We report the results of a comprehensive para-
metric study in an effort to establish a guideline and
criteria for an optimum wedge design. The conclu-
sions 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 dis-
placements detected by the transducer as the wave prop-
agates 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 con-
tact 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 ana-
lyze the performance of the wedge working as a partic-
ipating 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 recei-
ver, or both at the same time. For this, it is arguably suf-
icient 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 \( \Gamma_c \). 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 ra-
dius \( r \). This allows us to study the directional depen-
dency 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 con-
sidered. 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 \( (\Gamma_c) \) 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 sys-
tems, we use the boundary element method (BEM) be-
cause 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–speci-
men 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 bound-
ary condition. We use the classical conforming discreti-
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.

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 $A \rightarrow B$) at high frequencies.
The response is significantly improved for all frequencies in the spectrum.

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References