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TWO UTILIZATIONS OF OPEN RESONATOR CONCEPT IN NONDESTRUCTIVE TESTING

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Abstract: Two ways in which the concept of open resonator can be used in connection with nondestructive evaluation will be described. In the first, a non-contact transducer's efficiency of transferring energy into an object can be increased by utilizing the resonance of the gap between the transducer and object. By choosing the gap distance, frequency and transducer width a resonant wave appears which will have a considerably larger amplitude at the object surface. Secondly, by fitting the critical parameters of open resonators for thin objects, like extended plates, the wave field inside the object can be localized. Thus some Nonlinear Elastic Wave Spectroscopy methods may be used to determine the location of damage.

INTRODUCTION

Increasing the transferring of energy from noncontact transducers to objects is desirable for linear and nonlinear techniques. This is where the open resonator concept is first used by putting the airgap in resonance.

The second use comes from the desire to make the nonlinear ultrasound crack detection methods localizing the points or regions of the cracks. Therefore a short introduction into a non-linear ultrasound non-destructive testing method called Non-linear Wave Modulation Spectroscopy will be given. The method shows the non-linearity of the test specimen and can in that way detect cracks. It is at present non-localizing. Objects with limited geometrical shapes variations of many kinds can be investigated in a short time giving a damage estimation for the complete object. But the location of the damage is not indicated. Also for some particular objects like extended plates and long tubes, the whole object cannot be investigated in one sampling. The same is also important for structures like buildings, airplanes, cars, ships etc. where the complete structure cannot be tested in one single point. It is also needed to be able to test certain regions of the structures in order to know approximately the crack locations, and in order to avoid other known non-linear sources. Thus one should seek the criteria for exciting only a specific region. These two points of interest, the wave field and the localizing criteria, are in this work investigated for thin plates.

It is for these objects important to know in which region the crack might be and for this one needs to know the wave field distribution. In this article the wave field from an acoustic source in a plate is shown experimentally and numerically. Further, in order to obtain higher localization to a small region the concept of a standing wave in an open resonator is used.

One basic part of the nonlinear ultrasound methods, which are connected to the concept of Slow Dynamics [Guyer], is Nonlinear Wave Modulation Spectroscopy (NWMS). This nonlinear ultrasound method looks for the nonlinear generation of sum and difference frequencies from two simultaneously excited frequency components. This phenomenon can easily be seen in the spectrum where side bands occur close to the high input frequency component when having a damaged sample (see Figure 1). The advantage of these non-linear methods is that they are really sensitive also to micro-cracks. Another big advantage is that they react on cracks but not holes [see for example Kazakov]. The method is in its basic form non-localizing and shows only the total amount of non-linearity of the excited region (see Kazakov for an alternative of imaging).

The method can be applied in two different types of modes, continuous or impact mode, where in the continuous mode two sinusoidal waves are simultaneously input into the object with separate frequencies, one generating a low frequency signal and the other generating a high frequency wave. At a separate location on the object the interacted signals are recorded. For an intact object one can expect a spectrum containing only the two frequencies (peaks). For a damaged object one can expect the two original low and high frequencies and the sum and difference frequencies - the side bands, illustrated in Figure 1 (see [Johnson]).

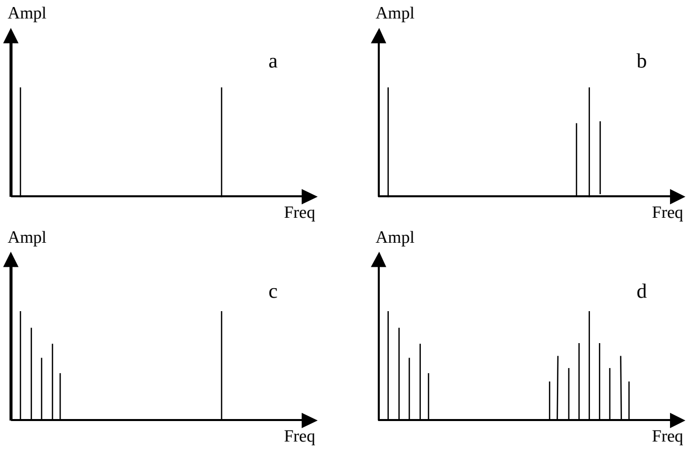

Figure 1.
Frequency spectra NWMS:
a) continuous mode non-cracked,
b) continuous mode cracked,
c) impact mode non-cracked,
d) impact mode cracked.

One problem with the continuous mode can be to get enough energy into the object, particulary in noncontact applications which is directly connected to the other part of this article.

By using impact mode the low frequency signal is generated by a hammer that is exciting the entire resonance mode frequency spectra. When having a damaged sample the side bands should have the look of the low resonance spectrum from the hammer hit, see Figure 1.

It is enough if one of the components, either the high frequency ot the low frequency, is localized. In this work the high frequency component will be localized.

RESONANCE

It is possible to create a high pressure with an open resonator in air [Arnoldsson]. The resonance can for example take place between two discs, one of which can be focusing (concave), or of course between a disc and a wall.

Most objects has a natural frequency at which it can self-oscillate, much the same as a string of a guitar vibrates with a constant frequency at a certain thickness and length. Also a volume of gas whose extent is restricted by boundaries may have natural frequencies at which it self-oscillates. In order to set a gas in motion there must be something that pushes it. This can be brought about with a moving surface. If the surface moves at the airgapÕs natural frequency it is called resonance and high amplitude waves normally form. A device or system which easily obtains high amplitudes is called a resonator.

The open resonator in this work consists of two surfaces. One of the surfaces vibrates actively and the other one is passive. The gas between the two surfaces is excited by the vibrating side and is reflected against the passive side, and the gas begins to oscillate.

When the gas is brought into resonance, a standing wave arises. Energy is temporarily stored in this wave. In practice, when the air is at its resonant frequency the result is a pressure increase in the air. If the resonant properties are large (Q-factor is large) the excitation and pressure increase creates a shock wave. The Q-factor is the quality factor telling how well an input signal is increased inside the resonator. The definition of the Q-factors [Enflo 2001] can be how many times the amplitude of the stationary wave is higher than the amplitude of vibration of the boundary.

Chester did important research in theoretically describing the shock waves around each resonant frequency, which was done in a closed resonator. He produced them at and near resonant frequencies through the oscillations of a piston at one end in a closed gas-filled tube. A more detailed description of the wave evolution in a closed resonator, can be found for example in the book Theory of nonlinear acoustics in fluids [Enflo 2002].

If the wave with wave speed *v* in amplitude bounces against a hard surface it is reflected and have the boundary conditions *v*=0, see figure 2 A. This is like the wave inside the airgap.

If the wave bounces against a soft surface it is inverted, see figure 2 B. This is equivalent to a pressure release boundary condition which is the case for the resonance inside the solid object.

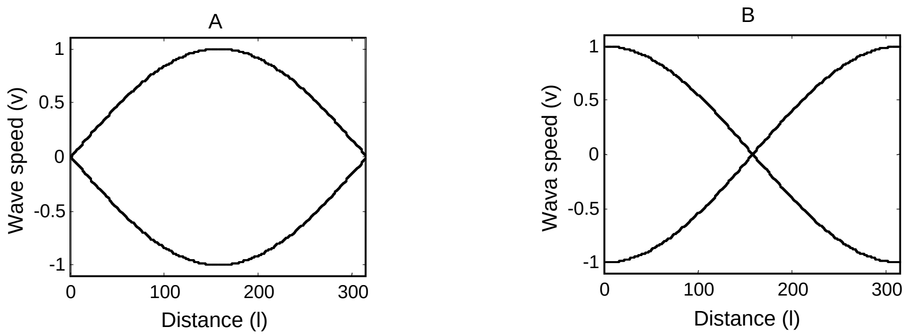

Figure 2. The wave speed along the resonator for the first mode shape at A: resonator wave for hard surface reflection, and B: for soft (pressure release) reflection.

If the wave with pressure amplitude *p* bounces against a soft surface it is reflected and have the boundary conditions *p*=0, see figure 3 B. If the wave bounces against a hard surface it is inverted, see figure 3 A.

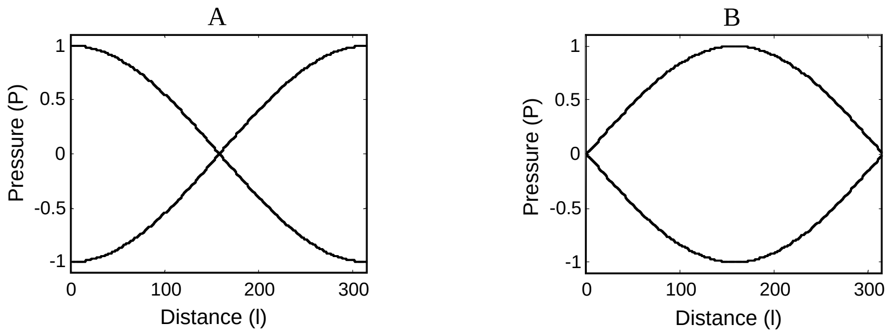

Figure 3. The pressure distribution along the resonator for the first mode shape at A: resonator wave for hard surface reflection, and B: for soft reflection.

OPEN RESONATOR IN AIR

In order to create a standing wave in a resonator the energy feed must be larger than the total losses until a high level of energy inside the resonator has been reached. For example, there are losses from attenuation and from spreading of the wave.

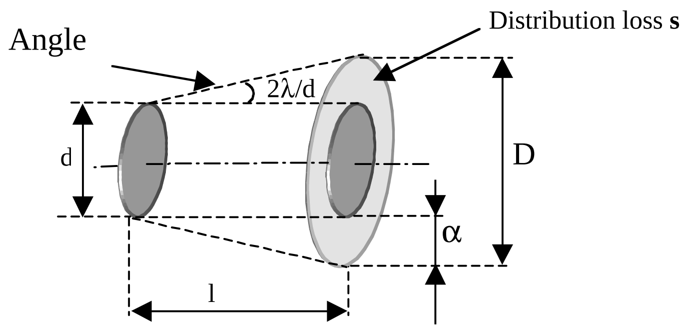

Figure 4. Sketch of an open resonator.

It is supposed that the wave energy is proportional to the area of reflection surfaces.

$$\frac{D^2\pi}{4} = \frac{d^2\pi}{4}(1+s) \Rightarrow D = d\sqrt{1+s} \qquad (1)$$

For the first standing wave in the resonator mode shape *n*=1, the length *l* is half a wavelength λ, formula 1.

$$l = n\frac{\lambda}{2} \qquad (2)$$

The boundary conditions from figure 4 for the distribution loss give the minimum diameter *d* of the resonator. D is the diameter of the distribution loss, and α is the difference between the diameter of the resonator and the distribution loss diameter gives:

$$\frac{2\lambda}{d} = \frac{\alpha}{l} \Rightarrow \frac{4l}{d} = \frac{(D-d)}{2l} \Rightarrow d = 10l \qquad (3)$$

The sound speed for the medium between the plates is c. The frequency *f* for standing waves for a resonator is:

$$f = \frac{c}{\lambda} = \frac{c}{2l}n$$

What happens if the glass platesÕeigen-frequency is the same as the air eigen-frequency? This was investigated showing that there could be a large pressure increase. Certain mode shapes of the glass plate are favourable for creating high pressure. [Arnoldsson]

Radial pressure for flat plates and concave plates

A measurement with two flat plates comprised of 29 measuring points indicating the maximum and minimum pressure radius at the transmitting plate about z=1 mm, where r is the distance to the centre.

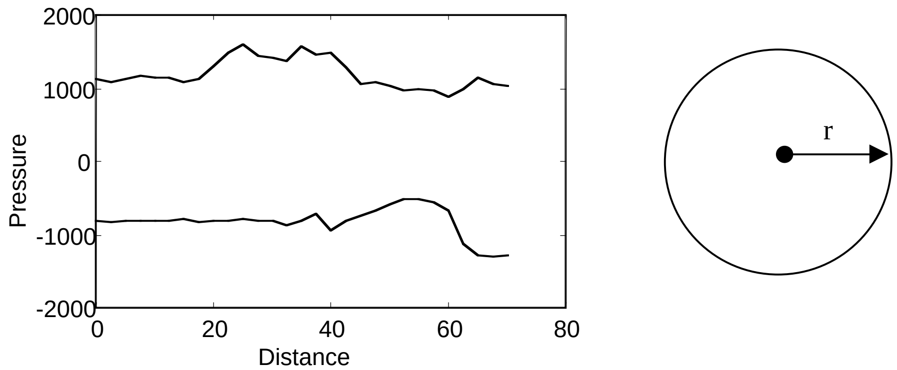

Figure 5. Measurement between two flat plates. Maximum and minimum pressure as function of radial position. BC: f_t = 8960 Hz, l = 19.60 mm, z=1 mm, r=0→70 mm.

Figure 5 displays the distribution of maximal and minimal pressure as a function of radius. Pressure is approximately the same along the radius.

The measurement for two concave plates comprised of 15 measurement points, which measured the maximum pressure distribution radius at the transmitting plate, where r is the distance to the centre.

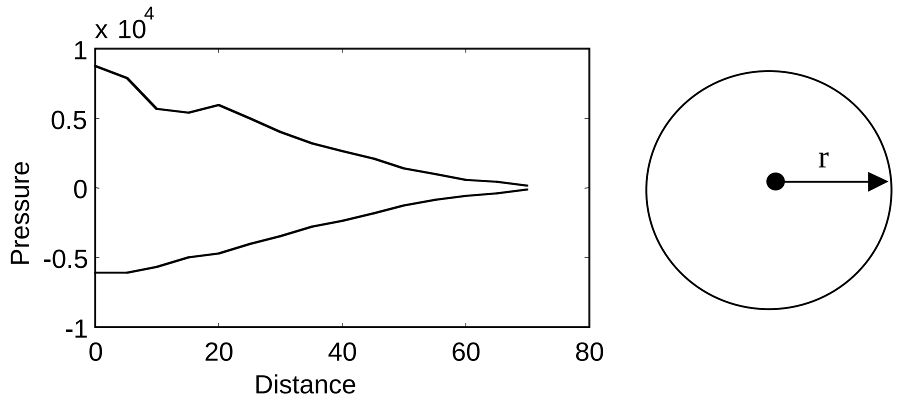

Figure 6. Measurement of maximum and minimum pressure as function of radial position. BC: f_t=8000 Hz, l=26.96 mm, z=1 mm, r=0→70 mm.

Figure 6 displays the distribution of maximal and minimal pressure as a function of radius. The highest pressure is found in the middle of the resonator and diminishes almost linearly with radius. This is in big contrast from the result with two flat plates in Figure 5.

The group of Gallego-Juarez has worked much on designing the active vibrators for this purpose with industrial application in mind. They have carefully investigated the sound field from the vibrating plate and adapted its design. [Gallego-Juarez]

The two flat surfaces have a shock wave and energy disappears in the shock. In the resonator with one flat and one concave surface, a wave closer to a sine wave appeared, more energy can be stored in the wave and the pressure was much higher.

STANDING WAVE FIELDS IN PLATES

To show that the (high frequency) wave field can be limited mainly to within a certain region, experiments were made and compared to mathematical simulations. Experiments were performed in a plexiglas of 5 mm. A 30 mm piezoceramic element was used as exciting transducer and a smaller one, diameter 10 mm, was used as receiver measuring the response on the opposite side. [Gunnarsson]

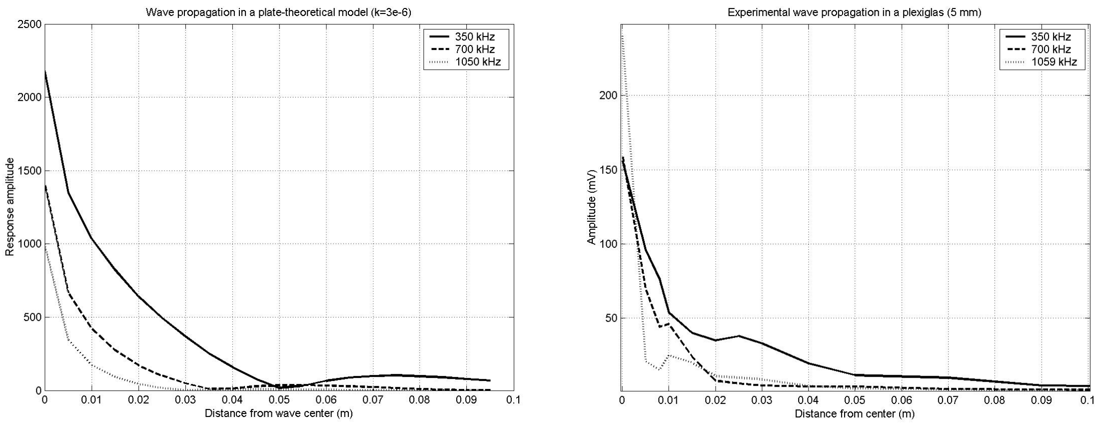

Figure 7. Wave propagation of three standing waves - simulation (left) and experiment (right).

Comparing the experimental wave propagation with simulated results, it can be seen that it works fairly good — Figure 7. The excited region is radially quite limited, in particular for the higher frequency.

The criteria for getting a limited area excited can be obtained in principle from the open resonator theory. In contrast to the open resonator in air described above, there is a reflecting area around the transducer which makes it possible to reach resonance at smaller diameters of the transducer. The mathematical model works satisfactory but damping is really hard to simulate and it also changes from material to material. Most important to note is that we are able to excite a small region of the plate and it can be useful when using some slow dynamics methods like nonlinear wave modulation in plates or similar structures.

CONCLUSION

We have shown two ways in which the concept of open resonator can be used in nondestructive testing: the resonance of the airgap between transducer and object increases noncontact energy transfer: and the standing wave localization possible in thin extended structures (like plates). These findings are useful in particular for some nonlinear ultrasound applications. Finally will be mentioned that both the applications might naturally be used simultaneously. The airgap between the transducer and the object can be resonating with a standing wave. This wave in turn excites the object where another standing wave is present in a region extending only a short distance radially from the transducer axis.

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