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Pseudo-Defects for the Validation and Tuning of Structural Health Monitoring in Plate-like Structures using Lamb Waves

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Abstract
In order to introduce SHM technology in real aircraft structures, new validation tests have to be in place. The present paper proposes an innovative technology where natural of artificial defects for validation could probably be replaced by pseudo-defects.
Keywords: Structural health monitoring, non-destructive testing, probability of detection, ultrasonic detection

1. Introduction

When new ultrasonic techniques for non-destructive testing are introduced, diverse validation tests are required. Signals obtained from samples with well-characterised natural defects (cracks, flaws) or artificial defects (notches, boreholes) are compared with signals measured at undamaged samples, and so the quality of the NDT technique can be assessed concerning reliability and accuracy. That concept finally leads to calibration procedures for ultrasonic systems. Distance/Gain/Size (DGS) - diagrams give an indication on the size of defects for flaw detectors, and dedicated test blocks are e.g. used to calibrate ultrasonic thicknesses gauges for different kinds of material [1].

The traditional procedures are however only applicable if relatively simple structures are present. If the structural complexity of the investigated samples is increasing, also the efforts for validation tests should increase. This appears usually to be the case for many structural aircraft parts for which applications of structural health monitoring (SHM) systems are discussed.

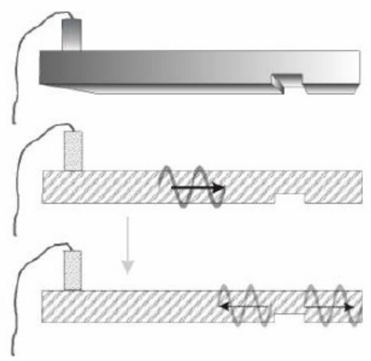
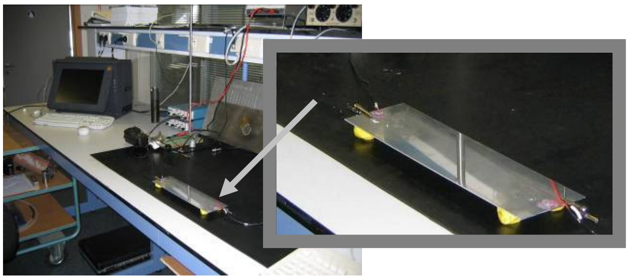


Fig. 1 Idealised representation of defect detection using guided ultrasonic waves (Lamb waves)

Due to the dominance of plate-like structures in aircraft, guided plate waves (Lamb waves) are interesting candidates for such automated inspection systems (Fig. 1). But there remains the inherent problem that guided waves have to be monochromatic due to the dispersive nature of Lamb waves. The approximate monochromacy results in signals that are represented by sinusoidal waveforms which are quite broad in the time and the spatial domain (typically consisting of 5-10 cycles) compared to the short pulses used in classic ultrasonics. The most appropriate frequency for Lamb waves is e.g. in the range of 400 kHz given aluminium sheets with a thickness of about 1 mm (see e.g. [2]). The corresponding group velocity of the appropriate s_0 mode is about 5400 m/s, and this yields a wavelength of about 13,5 mm. A waveform consisting of 5 sinusoidal cycles has therefore a spatial length of about 70 mm. However, in many aircraft structures, there are in a circle of about 10 cm almost no areas available without diverse “natural” reflectors (stiffeners, lap joints and rivets) hindering the free wave propagation of Lamb waves. This leads finally to multiple reflections that will interfere with the waves caused by real defects. Moreover, reflections are usually accompanied by mode conversions and this additionally complicates the analysis of experimental data. A typical example of such complex Lamb wave propagation in an aluminium sheet (Al 2024 –T3) is given in Fig. 2. This sample has about the size of a section of the aluminium plate present between different stiffeners in a fuselage structure. The left side shows the waveforms of the initial single burst and the resulting waveform received. The distance between sender and receiver is about 150 mm.



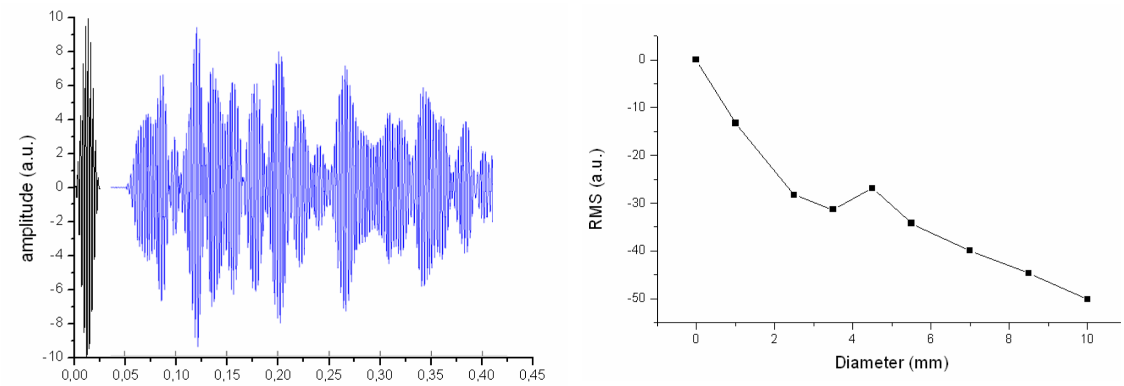


Fig. 2 Transmission of Lamb waves in Al 2024-T3 sheets. Left side: Initial burst (black) and resulting waveform received at the sensor – Right side: Relationship between the diameter of an artificial borehole and the root mean square value of the numerical difference of the waveforms with respect to the undamaged sheet.

It that specific case (Fig. 2, right side), it was even possible to establish a clear relationship between the ultrasonic parameter (RMS value of the numerical difference between the waveforms obtained for the damaged and the undamaged case) and the size of the artificial damage (diameter of boreholes). But in many cases, those relationships are much less obvious. This is one of the main reasons why the use of Lamb waves for the screening of large fuselage areas is still limited at this moment [3]. One could identify the following main problems in applying natural and artificial defects for SHM validation.

1.1 Probability of detection and advanced data analysis

The complex nature of ultrasonic signals (Fig. 2) obtained by SHM requires advanced data analysis. Here, diverse methods are available, such as neural networks and principal component analysis. These techniques usually require a big number of learning cases to train the respective mathematical procedures (see e.g. [4]). However, learning cases with real or artificial defects need a big number of experimental data whereby many full-scale parts would be consumed. This is very costly and extremely time-consuming. Moreover, this procedure would nevertheless provide a low level of reproducibility.

1.2 Challenges arising from the baseline method

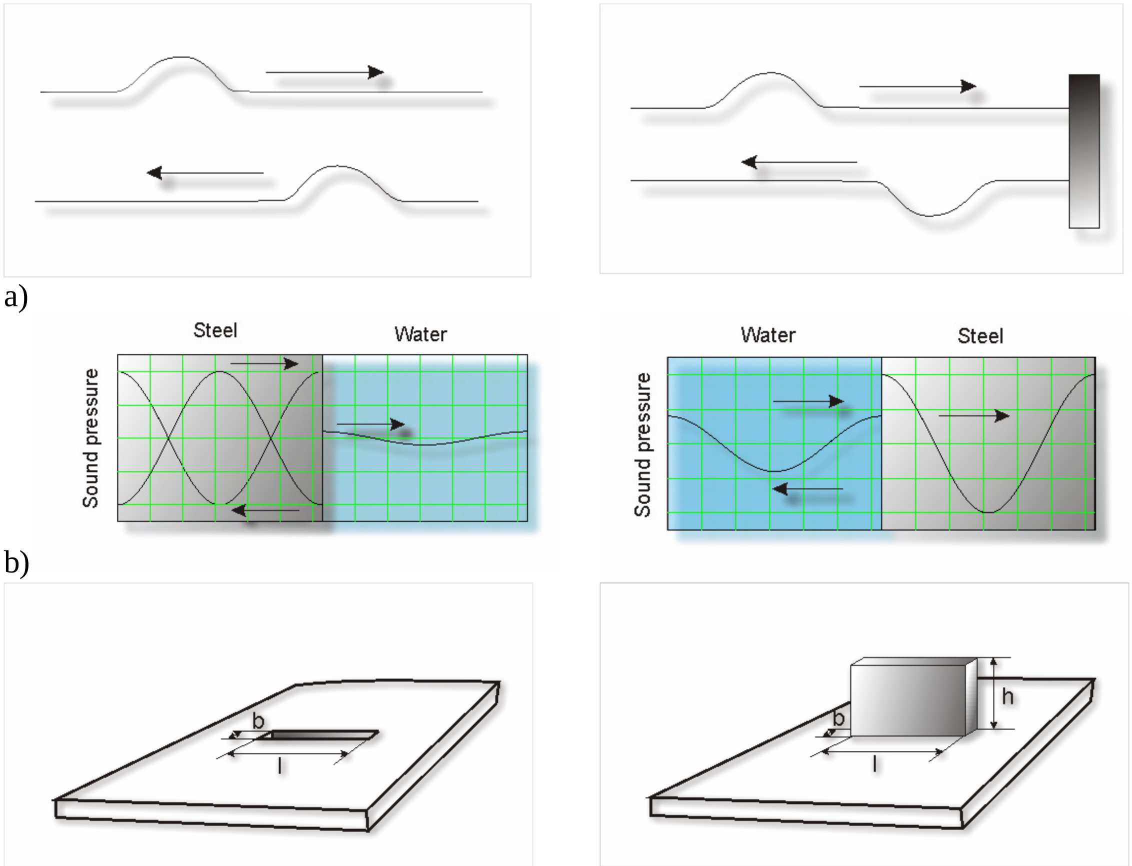
Due to the complex nature of the ultrasonic signals, signal analysis means in many cases that incremental changes of the signal with respect to a reference measurement are analysed (baseline method). Also in the case reported above (Fig. 2), the numerical difference of the waveforms was used for damage analysis. This is in contrast to classic ultrasonic NDT, i.e. the traditional determination of e.g. the material thickness or the damage size must be possible, independent of earlier data determined at the same undamaged sample. In the case of SHM it is thus important to perform measurements of the undamaged or less damaged part in order to follow-up the progress of the degradation process to obtain some kind of novelty parameters. It is self-evident that every complex part shows its own baseline behaviour, and therefore, the baselines and defect parameters obtained at the validation phase must not necessarily be valid for the respective structure in another aircraft. The baseline method thus challenges even the principle feasibility of the validation of SHM by artificial or real defects.

2. Basic concept of pseudo-defects and some theoretical considerations

Defect detection follows the concepts shown in Fig. 3. Waves interact with defects and this leads to specific reflection and transmission characteristics. Classic detection by pulse-echo can in a first approximation be explained by the reflection of a plane wave at the interface between sample and air/vacuum (or sample and water) whereby the defect is represented by the volume with the lower acoustic impedance. This is analogous with the rope reflection at a lose end.

The basic idea presented here is to replace real defects by non-destructively applied pseudo-defects. To achieve this, the material is subjected to a non-destructive modification. In the present case, this is done by two blocks that are modestly pressed onto both sides of a thin plate. This material modification leads to specific reflection and transmission characteristics which could be similar to certain real defects, if the dimensions of the blocks are adequately chosen. Such as in the case of real defects, the reflection at artificial pseudo-defects is in principal correlated with local changes of the acoustic impedance.

Non-destructively applied pseudo-defects potentially enable a huge number of learning cases for advanced data analysis of ultrasonic data when testing objects are too rare, too complex or too expensive. The principle is illustrated in the lower plot of Fig. 3. At the left side, a natural crack in an infinite aluminium plate with a defined thickness, d is modelled by an artificial notch with the length l and the width b. The corresponding pseudo-effect would be blocks with a height *h* which is pressed onto both sides of the surface having the respective dimensions *l'* and *b'*. The principal question is which dimensions *l'*, *b'* and *h*, the blocks must have to approximately match the ultrasonic response of the real defect having the dimensions *l* and *b*.



c)

Fig. 3 Real notch and pseudo-defect for creating similar reflections.

A principal difference is that the reflection of the wave at a real defect is due to the difference of impedances between the structural material and the air/vacuum. In the case of the pseudo-defect, the wave is reflected at the difference of impedance between an aluminium plate and a structure that could even represents a higher acoustic impedance. Furthermore, the impedance difference will also depend on the frequency and the Lamb mode selected, and also mode conversion has to be considered.

2.1. Reflection and transmission of plane waves

The reflection and transmission of plane waves such as illustrated in the middle plots in Fig. 3 can easily be described by appropriate reflection and transmission coefficients [1, 5]. The reflection and transmission coefficients can be defined using the ratio of the incident, reflected and transmitted sound pressures, p_i, p_r and p_t, respectively (Eq. 1):

$$R = \frac{p_r}{p_i} \text{ and } D = \frac{p_t}{p_i} \qquad \textit{Eq. 1}$$

These coefficients can also be expressed by the acoustic impedance, Z, which is defined by:

$$Z = \rho c \qquad \text{Eq. 2}$$

Here, ρ and c are the density and the sound velocity resp.. The resulting equations are (Eq. 3):

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2} \text{ and } D = \frac{2Z_2}{Z_1 + Z_2} \qquad \text{Eq. 3}$$

The indices, 1 and 2 refer to the materials at both sides of the interface.

2.2. Reflection and transmission of Lamb waves

The reflection and transmission of Lamb waves is much more difficult to describe. One of the problems arises from the fact that guided waves can be considered as superpositions of numerous elementary waves that irradiate the material interfaces at different angles. This gives reason to all different kind of mode conversions. In the case of Lamb waves, the reflection coefficients are a function of the wave number, *k*, and the plate thickness, *d*, and normally, reflections coefficients are in most cases smaller than 1, even in the case of edge reflections [6]. There are however situations when the reflection coefficient could be approximately 1, and this situation is essential in order to have strong signals arising from such real defects. In order to find high reflection coefficients, it is important that a number of conditions are fulfilled. The most important condition is that one of the stresses at the interface of the edge of the aluminium sheet is much larger than the others. For a more detailed analysis of the reflection of Lamb waves at defects see also e.g. [5, 7, 8].

Until now, we did not find any literature referring to systematic studies on such pseudo-defects to be used in SHM validation tests. But we might have a look at similar studies that were published addressing the theoretical and experimental treatment of similar cases. Song et al. [9] considered the scattering of Lamb waves at plate overlaps. The corresponding reflection and transmission characteristics show indeed strong dependency on frequency and Lamb mode. Practical NDT applications thus require thorough tuning to find optimal reflection and transmission conditions. Similar conclusions were drawn in a study on thickness variations in thin sheets [10] and Lap shear adhesive joints [11]. The strong dependency on frequency shows that tuning is an essential part during the establishment of baselines.

3. Materials and Methods

In order to perform a first proof-of-concept, we used an aluminium plate with a side length of 1 m so that disturbing side wall reflections could be avoided. Piezoceramic patches were adhesively attached to the aluminium plate by cyano-acrylate glue (M-Bond 200). The optimum frequency is in the range of about 400 kHz. In this region, the s_0 mode will be excited and according to the dispersion curve (next figure), one can expect a group velocity of about 5400 ms. The resulting wavelength would be of the order of 13,5 mm. In order to check the detection capabilities with respect to defect locations, 9 piezoelectric transducers were arranged in one line so that they could be used in a passive phased-array mode (comparable to [12, 13]). The sensors (APC ceramics) had a thickness of 0,2 mm and a side length of 7 mm, and the distance between the sensor was 9 mm which is approximately in the range of a half wavelength.

The actuators were driven by an arbitrary waveform generator (GAGE – waveform generator) at a frequency of 400 kHz. The output signal consists of Hanning-windowed bursts (5 counts at an output voltage of 10 V_{pp}). The signals were received by the respective sensors and used without pre-amplification. The GAGE card was used as an AD receiver and there was a band-pass filter (300-500 kHz) applied. The signal was recorded with a sampling rate of 5 MHz. The whole set-up was processed by a home-made Labview programme. The central transducer has sent the signals, and the wave forms were sequentially received by the other 8 sensors. From the signals, a 2D plot was derived.

4. Results and discussion

Fig. 4 Mechanical application of non-destructive pseudo-defects on an aluminium plate

Fig. 4 shows the wired sensor array and the mechanical equipment used to establish a tough connection of two blocks with the aluminium plate. The blocks were iron cubes with a side length of 2 cm. It appeared that the pressure applied to the blocks had no influence on the reflection pattern once a certain pressure threshold was reached. This indicates that the geometrical shape and the material of the blocks dominate the reflection behaviour.

Firstly, the sensors were checked and due to the different positions, the group velocity in the array region was determined to be about 5020 m/s (Fig. 5). This value is important for the mathematical procedure to determine the position of the pseudo-defect using the 2D plot.

The most important feature is that the pseudo-defect gave a clear echo that completely disappeared when the pseudo-defect was removed (Fig. 6, left side).The pseudo-defect was attached at different positions and also the orientation of the blocks was varied. One can imagine that the ultrasonic response can be determined for a huge number of positions and geometrical sizes. The detection of the position is possible by the use of the 2D plot (RADAR) picture.

This early step in developing an alternative validation system must be continued by a theoretical, numerical and experimental studies.

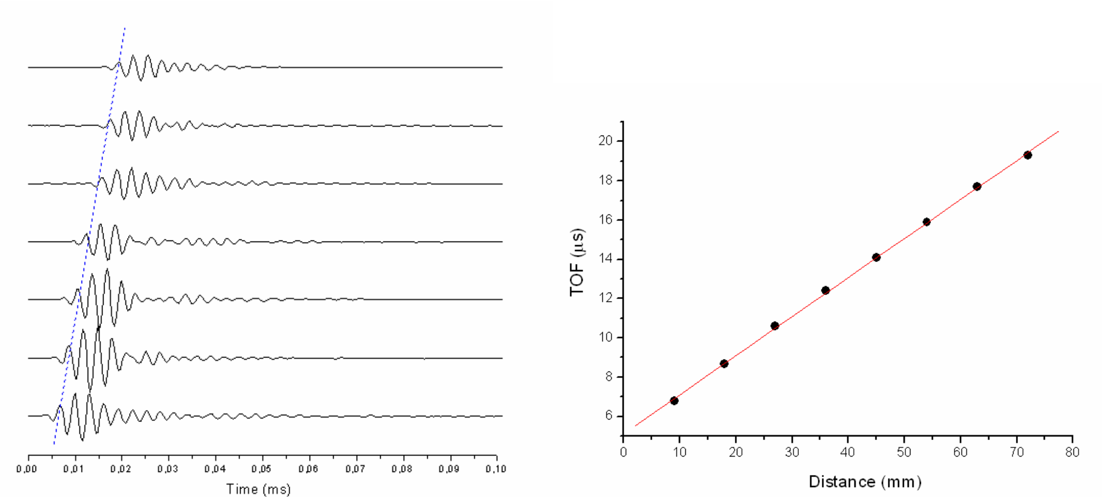


Fig. 5 2-D Determination of the group velocity using the different sensors of the phased-array sensor

One should not assume that pseudo-defects, affecting the same area such as real defects, provide similar reflections. It is more interesting to see the trends of how the incremental change of respective dimensional parameters are related to each other, i.e. what is the relationship between δl and $\delta l'$ as well as δb and $\delta b'$ at different *h*. This should lead to a library where clear assignments between the ultrasonic signals of real defects and its respective pseudo-defects are possible. The final goal is to establish a mapping for the probability of detection at different positions at an aluminium plate.

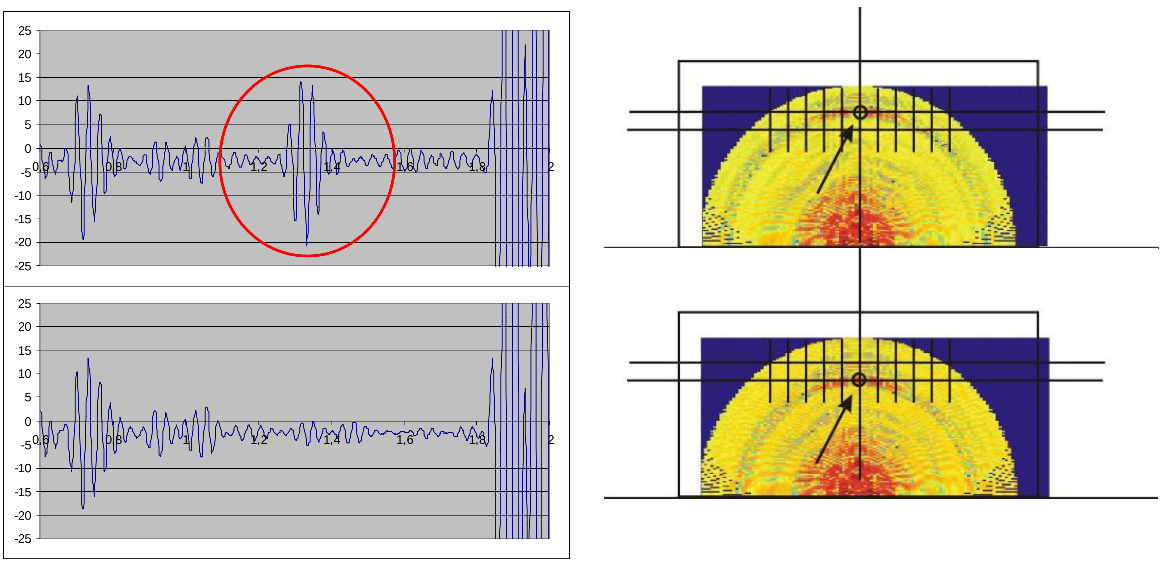


Fig. 6 Left side: Pulse-echo signal during application of the pseudo-defect and after removal. The red circle indicates the reflection from the pseudo-defect. - Right side: 2-D "Radar" picture of the pseudo-defects applied to an aluminium plate detected by an 8-element SHM phased-array transducer adjusted for Lamb waves. The applied pseudo-defects are indicated by arrows.

In a final step, the application of pseudo-defects should be completely automated to enable a completely controlled validation process. A sufficiently dense grid of pseudo-defects applied with different geometric symmetries results in a huge number of signals that will train the detection capabilities of the advanced data analysis tools of the respective SHM system for individual aircraft components.

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References

1. J. Krautkrämer and H. Krautkrämer, Ultrasonic Testing of materials, Springer, Berlin, 1990.
2. V. Giurgiutiu, Tuned lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring J. Intell. Mater. Syst. Struct. 16 (2005) 291-305.
3. R.P. Dalton, P. Cawley and M.J.S. Lowe, The potential of guided waves for monitoring large areas of metallic aircraft fuselage structure J. Nondestruct. Eval. 20 (2001) 29-46.
4. W. Staszewski, C. Boller and J.R. Tomlinson, Health Monitoring of Aerospace Structures: Smart Sensor Technologies and Signal Processing, Wiley, Chichester, 2004.
5. J.L. Rose, Ultrasonic waves in solid media, Cambridge University Press, Cambridge, 1999.
6. I.A. Viktorov, Rayleigh and Lamb waves, Plenum Press, New York, 1967.
7. P. Fromme and M.B. Sayir, Detection of cracks at rivet holes using guided waves Ultrasonics 40 (2002) 199-203.
8. S. Grondel, C. Delebarre, J. Assaad, J.P. Dupuis and L. Reithler, Fatigue crack monitoring of riveted aluminium strap joints by Lamb wave analysis and acoustic emission measurement techniques NDT E Int. 35 (2002) 137-146.
9. W.J. Song, J.L. Rose, J.M. Galan and R. Abascal, Ultrasonic guided wave scattering in a plate overlap IEEE Trans. Ultrason. Ferroelectr. Freq. Control 52 (2005) 892-903.
10. K. Cho, J. L., Estimation of ultrasonic guided wave mode conversionUltrasonic waves in a plate with thickness variationsolid media IEEE Trans. Ultrason. Ferroelectr. Freq. Control 47 (20001999) 591-603.
11. S.I. Rokhlin, Lamb Wave Interaction with Lap-Shear Adhesive Joints - Theory and Experiment J. Acoust. Soc. Am. 89 (1991) 2758-2765.
12. V. Giurgiutiu and J.J. Bao, Embedded-ultrasonics Structural Radar for In Situ Structural Health Monitoring of Thin-wall Structures Structural Health Monitoring 3 (2004) 121-144.
13. J. Peña, C.P. Melguizo, R. Martínez-Oña, Y. Gómez Ullate, F. Montero de Espinosa Freijo and G. Kawiecki. in Third European Workshop on Structural Health Monitoring, Granada 2006.