Ultrasonic Lamb Wave Inspection of Aircraft Components Using Integrated Optical Fibre Sensing Technology

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Abstract. As continuous health monitoring of aircraft components will provide substantial time and cost savings to the aircraft industry, the use of an integrated sensing technology with autonomous damage assessment is looked for. This study is part of the 6th STREP framework AISHA project, investigating the use of ultrasonic Lamb wave technology for the fast inspection of large shell structures. For the detection of the generated ultrasonic Lamb waves and their alterations due to damage, single mode (SM) optical fibres embedded in a SMARTape and glued on a structural part or embedded in the composite have been used. This paper presents the different ways the optical fibre sensor is implemented in order to detect typical Lamb waves, symmetric and antisymmetric, propagating in a metallic and a composite thin walled structure. One important basic property of Lamb waves is their dispersive nature: the velocity of propagation of a Lamb wave is dependent on its frequency, or to be more specific, on the product of the frequency and the plate thickness. The detection of material damage is based on the fact that the propagation is affected by the presence of damage due to the environmental conditions or caused by mechanical loading like impact or fatigue damage. The influence of these degradation mechanisms upon the signal from the optical fibre sensing the Lamb wave in a composite plate-like structure is investigated. Quantitative correlations between the monitored transient signals of the optical fibre and the type and extent of the damage are established.

Introduction

Since Lamb waves are guided waves that propagate between the surface boundaries of shell-like structures over large distances without substantial attenuation, they are very suitable for the use in health monitoring applications [1]. In order to profit most from these characteristics, the use of actuators and sensors which give integrated structural information is favoured. In contrast to point transducers, optical fibre sensors can monitor large areas without the need to cover the structure with an enormous amount of sensors [2]. Single mode (SM) fibres are also cheap, don’t require highly specialized expensive equipment and are insensitive to magnetic and electrical interferences. For this project they have already been successfully used, as did others in several other Lamb wave applications [3] [4] [5].

The intrinsic SM optical fibre sensor can be configured as an interferometric, a polarimetric or an intensity sensor [6]. The interferometric sensor is reported to be much more sensitive than the intensity modulated sensor [7], but requires a well-isolated and undisturbed reference arm which is difficult to yield.

In this paper a polarimetric approach is used, where the intensity change that is due to the induced phase shift, is monitored. This is in contrast with other research where the phase shift itself is being monitored. In that case the polarimetric sensors will detect the perturbation of the acoustic field by monitoring the change in the state of polarization of the light propagating through the fibre. Polarimetric sensors require a much simpler setup, though generally a lower resolution is achieved. This type of sensor has been widely used to measure for instance hydrostatic pressure [8], ultrasonic fields [9], weight [10], current [11], damage [5] [12] [13] and to perform biochemical measurements [14].

Single Mode Fibre in a Polarimetric Setup

A. Detection Concept

When not subjected to external influences, two linear orthogonal modes can propagate through a single mode (SM) fibre at the same velocity. However, when an incident ultrasonic wave interacts with the fibre it becomes anisotropic. The ultrasonic pressure on the fibre alternates the refractive indices of the two orthogonal optical axes, causing the two polarization eigenmodes to travel at different velocities and accordingly inducing a phase difference. This birefringence will cause variations in the polarization at the output of the fibre which depend on the ultrasonic pressure that is imposed onto the entire length of the SM fibre [4]. Thursby et al. [5] describe such a polarimetric setup for the detection of changes in the polarization state for the detection of damage in flat specimens.

This research focusses on the use of a photo detector to monitor changes in the light intensity caused by the birefringence. The polarizer at the output of the sensing fibre isolates a particular polarization state. The intensity of the light travelling according to this state varies due to phase shifts in the two optical axes. The change in intensity is an integrated response of all the phase dependent changes along the length of the fibre sensor.

B. Experimental Setup

In the frame of this research programme different material types are used for the validation of the monitoring setup. The selection of these materials is based on their relevance to the aircraft industry. Experiments are conducted on metals such as Al 2023 T3 and composite materials such as quasi-isotropic carbon/epoxy plates using 1000g/sqm +/-45° UD carbon for the inner layers and 900g/sqm 0°/90° woven carbon fabric for the outer layers. All sheets are made of 120°C HT carbon prepregs.

Figure 1 shows the setup that is used for the detection of impact damage on flat lab-scale specimens. The optical fibre sensor is connected to an ANDO AQ4141B stabilized laser source which sends light (wavelength = 1310 nm) through an isolator (Newport Isolator) into the sensing fibre. A polarization controller (Fiber Control Industries FPC-3) is placed between the laser source and the fibre sensor to optimize the input polarization in order to achieve optimal fringe visibility. The light then passes through a fibre polarizer (OZ Optics FOP) before being transmitted to a photo diode. The photo diode detection unit is coupled to a laser amplifier (UDT-1200A) and a filter/amplifier (Krohn-Hite Model 3988) which transmits the filtered and amplified signal to an oscilloscope (LeCroy 9310AM) and a PC-controlled read-out unit where it will be progressed and analyzed.

The Lamb waves are excited with piezo-electric patches that have been glued onto the specimen surface with acrylic glue. These patches are thin (500 µm), cheap and easy to handle, which makes them very suitable for the use in the envisaged health monitoring applications. The piezo patches can be glued to metallic parts with conductive epoxy glue, which offers both a conductive and strong adhesion. Ground cables can then be attached to the sample surface. For composite materials, a thin copper film is glued to the bottom of the piezo-electric patch to ensure an easy connection to the ground cable. The patch with copper film can then be glued to the sample with a regular epoxy adhesive. The patches are driven by a waveform generator (Agilent 33250A).

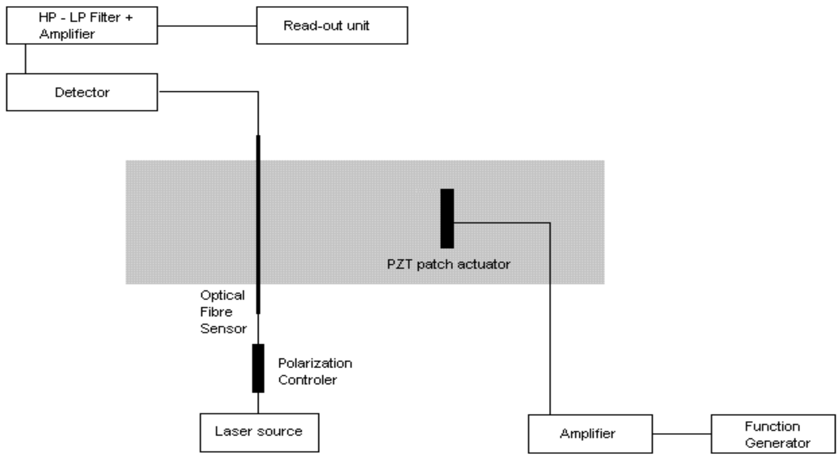


Figure 1. Single mode optical fibre sensor in a polarimetric setup for the detection of impact damage

The main advantage of the optical fibre sensor is the ability to monitor the signal over the whole width of the specimen. Single mode fibres typically have low attenuation so the optical signal can be transported over several meters without loosing much of its sensitivity. In addition, the received signal is the integrated response over the whole length of the sensing part of the optical fibre sensor, which makes this setup less dependent on local constructive or destructive interferences in the Lamb wave propagation pattern as is the case for point sensors. The use of piezo patches of a 50 mm width also contributes to this effect, since they emit a more beam-like wave whereas point sensors emit a radial wave front which will more often lead to side edge reflections.

Sensor/Actuator Integration

The integration of the sensor/actuator onto the structural part to be monitored is very crucial in online detection applications. The sensors/actuators should be kept as small as possible in order to preserve the mechanical and structural integrity of the component. Surface mounting and embedding (only for composite materials) of the sensor/actuator are two possible ways to integrate the monitoring system into the structure.

Several optical fibre sensor integration methods are compared in the following paragraph. To simplify the handling of the fragile and brittle optical fibres during the sample preparation, it was preferred to use the SMARTape optical fibre sensor manufactured by the company SMARTEC from Manno, Switzerland. It is a PPS/glass fibre composite tape with an embedded optical fibre (see figure 2 and 3). This thermoplastic composite tape also protects the optical fibre from external mechanical or chemical influences which could possibly damage the optical sensor in service or during the manufacturing of the composite material with embedded fibre.

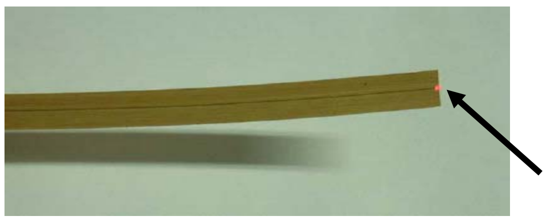


Figure 2. Picture of the SMARTape optical fibre sensor with visible light. [15]

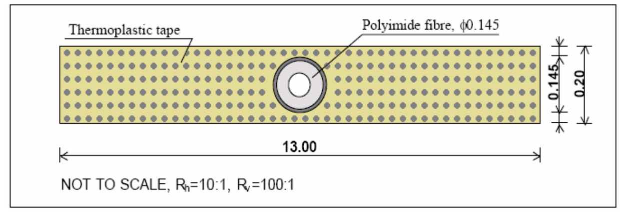
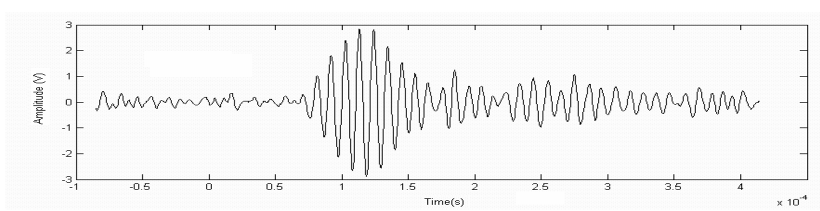


Figure 3. Cross-section of the SMARTape optical fibre sensor. [15]

With the use of a SMARTape optical fibre sensor a recording is made of a 5 cycle sine burst signal that is transmitted into a carbon/epoxy specimen. The signal is compared with one that is recorded by a conventional piezo transducer at the same instance. Both signal recordings signals show good agreement with each other as can be seen in figure 4. The signal-to-noise ratio of the optical fibre sensor is lower than that coming from the piezo transducer. But although the optical fibre sensor has a lower sensitivity compared to the piezo transducer, the incident wave is clearly visible. The signal typically consists of a main burst arriving first, followed by several front-to-back edge reflections which will not be investigated for the damage detection. However, since the propagation distance can differ slightly according to the followed path from transducer to sensor (with or without side edge reflections), the received main burst shows more cycles than the originally emitted burst. Note, the optical fibre signal appears to have a higher absolute amplitude (3 V) than the conventional transducer signal (80 mV), but this is due to the extra amplification of the signal in the optical detection setup.

a.



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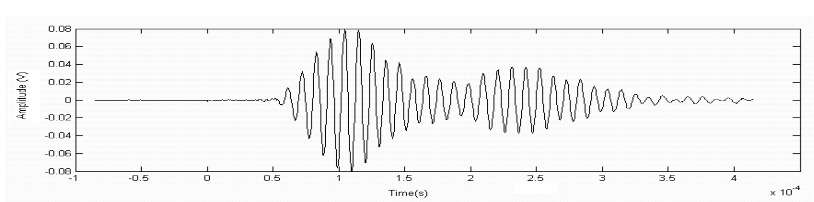


Figure 4. Signal recorded in a carbon/epoxy specimen after excitation of a 5 cycle sine burst at 100 kHz: a. Signal recorded by a SMARTape sensor; b. Signal recorded by a conventional piezo transducer.

Figure 5 depicts different optical fibre integration methods that were studied. All experiments are carried out on quasi-isotropic carbon/epoxy samples. For all four integration methods a series of impact tests have been carried out, analyzing the received Lamb wave signal. The impact energy, and therefore also the damage, is step by step increased during the experiments.

Figure 5. Different fibre integration methods: a. Surface mounted SMARTape sensor; b. Embedded SMARTape sensor; c. Embedded locally stripped SMARTape sensor; d. Embedded bare optical fibre sensor.

All integration methods show a decreasing trend with increasing damage and are therefore suitable for the detection of impact damage. However big variations in the amplitude ratio and hence in the sensitivity of the detection can be discovered, which is shown in figure 6.

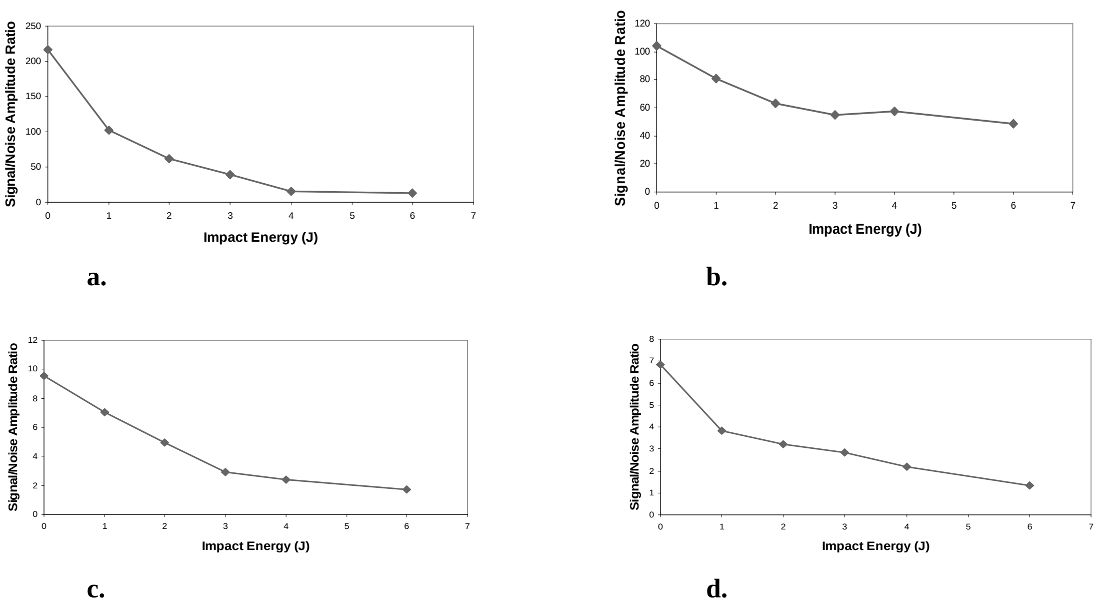


Figure 6. Curves showing the signal-to-noise amplitude ratio as a function of the impact energy: a. Surface mounted SMARTape sensor; b. Embedded SMARTape sensor; c. Embedded locally stripped SMARTape sensor; d. Embedded bare optical fibre sensor.

The differences in sensitivity can be explained by the difference in acoustic contact between the monitored specimen and the optical fibre sensor. The whole area of the SMARTape is in contact with the wave (cases a and b), which leads to much higher signal-to-noise ratios when compared with cases c and d where the bare optical fibre is in contact with the specimen. In addition, in cases b, c and d are fibres embedded at the central neutral axis, between the 90° layers. This has been found to be least disturbing to the mechanical integrity of the material because the fibre sensor is then in line with the surrounding reinforcing fibres [16]. This can also lead to lower signal amplitudes because symmetric Lamb waves typically show less particle movement at the central in plane axis.

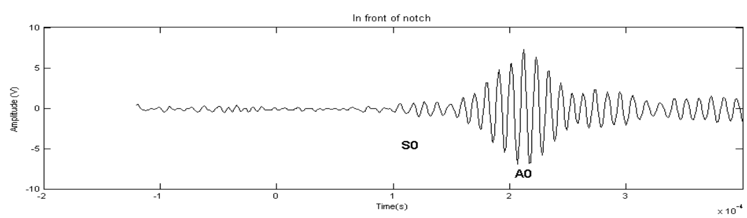
Surface mounting the SMARTape sensor does not only result in the highest sensitivity, it is also the easiest way to integrate the monitoring sensor into the structure. In order to provide a proper bonding between the sensor and the specimen a suitable adhesive has to be chosen which is able to withstand all external influences such as vibrations, temperature gradients, elevated humidity, etc. It is highly important to keep the adhesion between the sensor and the structure to be monitored optimal in all flight conditions because detachment of the sensor leads to lower signal amplitudes which may be falsely interpreted as a degradation of the structure itself.

Damage Detection in Metallic and Composite Plate Structures

A. Detection of a Notch in a Metallic Plate

For the detection of an artificial notch over the whole width of a large aluminium plate (dimensions 1000x200x2 mm), two SMARTape sensors are glued to the surface of the specimen. The notch is located between the two optical fibre sensors so that the difference between the two received signals can only be due to the effect of the notch on the propagation of the ultrasonic waves. A conventional piezo transducer is used to excite the Lamb waves by emitting a 5 cycle sine burst of 100 kHz.
In figure 7 the resulting signals are shown. It is clear that both the S_0 and the A_0 mode are attenuated by the notch. A similar behaviour can be found in the time frequency curves in figure 8 which are calculated from the same received signals.

a.



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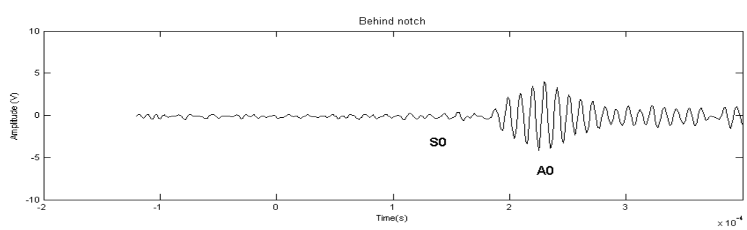

Figure 7. Signals received in a notched aluminium plate: a. Signal received in front of the notch; b. Signal received behind the notch.

a.

b.

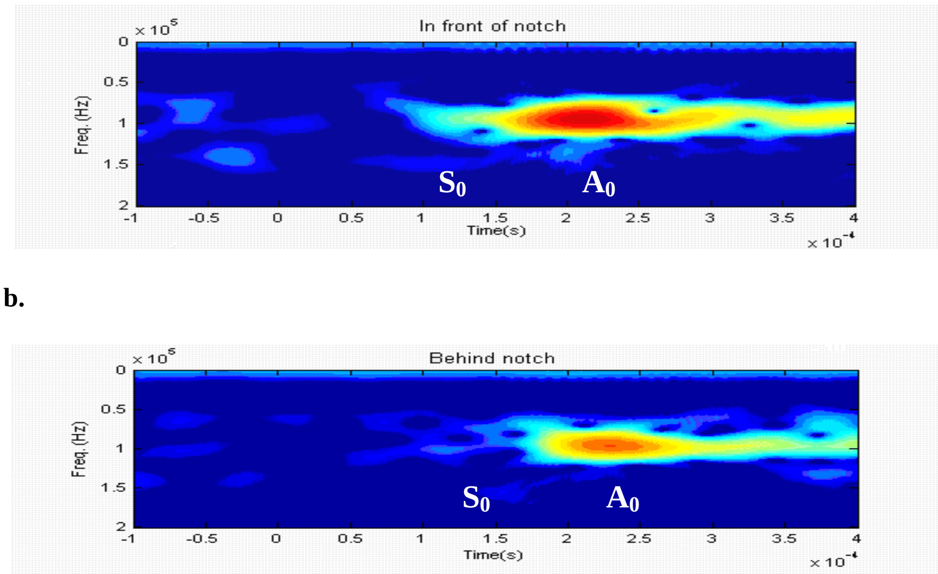

Figure 8. Time-frequency spectrum of the signals received in a notched aluminium plate: a. Signal received in front of the notch; b. Signal received behind the notch.

B. Detection of Impact Damage in a Composite Plate

The monitoring setup is also used to observe the changes in the Lamb wave signal after a series of drop-weight impact tests that are performed on carbon/epoxy samples (dimensions 300x100x2.1 mm).

To analyse the energy that is transmitted by the Lamb waves through the sample, the root-mean-square (RMS) value of the time-gated signal is used. The RMS value of the noise is used as a reference, so that the signal-to-noise ratio (SNR) can be defined as follows:

$$SNR = \frac{RMS_{BURST}}{RMS_{NOISE}} = \frac{\sqrt{\frac{\sum_i n_{i\,BURST}^2}{i}}}{\sqrt{\frac{\sum_j n_{j\,NOISE}^2}{j}}}$$

A piezo patch is used to excite the specimen with a 5 cycle sine burst of 82 kHz. Figure 9 shows a curve that illustrates the SNR as a function of the impact energy that is released onto the specimens. The ultrasonic wave that interacts with the optical fibre sensor decreases in energy when the impact energy is increased. The higher the impact energy the more the damage state is developed, which reduces the energy content of the arriving Lamb wave due to scattering, absorption and reflection.

This approach is less influenced by the many edge reflections that arise in small plate samples. Because the edge reflections give rise to complicated interference patterns in the Lamb wave propagation, even a small change in the location of a point sensor could lead to a large difference in the received signal. The optical fibre sensor however returns an integrated response over the whole width of the specimen, which is much less influenced by the interferences.

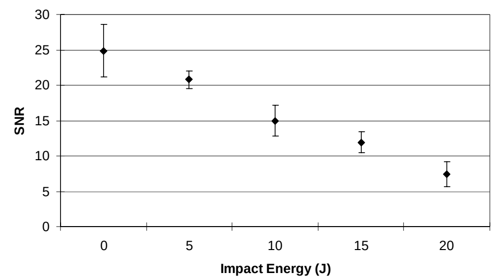

Figure 9. Curve showing the RMS-based SNR for quasi-isotropic carbon/epoxy samples impacted at different energy levels.

Figure 10 shows the results from ultrasonic C-scan measurements that were performed with the HFUS 2000 apparatus (Ingenieurbüro dr. Hillger), an IAP-FS 50.2.1 sensor (KrautKrämer 50 MHz), a digital oscilloscope (LeCroy 9400A dual 175 MHz) and a PC with own developed software.

The calculated damaged areas show an increasing trend as the impact energy is increased. However, the standard deviations (shown by the error bars) are similar or even bigger than in the case of the Lamb wave measurements shown in figure 9. Even though the ultrasonic C-scan is a widely and frequently used technique, it can not provide more consistent results than our newly developed monitoring technique.

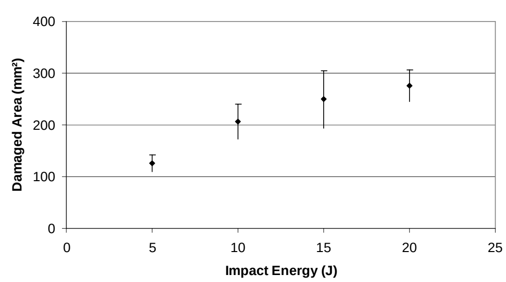

Figure 10. Curve showing the damaged areas calculated from ultrasonic C-scan images for quasi-isotropic carbon/epoxy samples impacted at different energy levels.

Conclusion

Optical fibre sensors can be used in different setups for the detection of structural damage. This paper presents the use of a single mode optical fibre sensor in a polarimetric setup for online health monitoring applications with active Lamb wave inspection. It is shown that different damage types in both metallic and composite materials can be detected by monitoring the variations in the light intensity transmitted by the optical fibre. Since the optical fibre sensor delivers an integrated response it is hardly influenced by edge reflections and the resulting complex interference patterns, which is in contrast with point sensors. When performing impact tests on composite samples with increasing damage states, the optical fibre signal shows a decreasing trend in the signal-to-noise ratio. Standard deviations are not larger than for the nowadays commonly used ultrasonic C-scan methods. These consistent test results are very promising for the establishment of quantitative correlations between the extent of the damage and the signal. New tests already initiated to monitor fatigue damage have also yielded some good results. Future work includes further fatigue testing on the quasi-isotropic carbon/epoxy specimens, and impact/fatigue testing on carbon/epoxy sandwich specimens with both foam and Nomex® cores.

Acknowledgements

All experiments have been carried out in the frame of the 6th Framework STREP project nr. 502907: Aircraft Integrated Structural Health Assessment (AISHA). We wish to thank all our partners for their support: METALogic, Leuven, Belgium; Deutches Zentrum für Luft- und Raumfahrt (DLR) - German Aerospace Centre, Braunschweig, Germany; Riga Technical University, Riga, Latvia; Eurocopter, Marignane, France; Cedrat Technologies, Meylan, France; Centro de Tecnologías Aeronáuticas (CTA), Miñano (Álava), Spain; ASCO, Zaventem, Belgium

We also wish to thank SMARTEC, Manno, Switzerland for providing the SMARTape fibre sensors.

This research was conducted with the dedicated help from Ing. Johan Vanhulst of K.U.Leuven-Dept. MTM.

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