Structural Health Monitoring of Composite Fan Outlet Guide Vane

Detecting damages and impacts using piezoelectric wafer active sensors and Lamb waves

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Abstract

The use of composite materials within the aerospace industry has increased in the last decades and is still on the rise. Most composite applications are in the aircraft body parts but engine components such as fan blades and fan outlet guide vanes (FOGV) are now also to be found. Metals are well studied and both their fatigue and cracking behavior are well known but for composites this is not the case. Composites also have problems such as micro-cracking, delamination and porosity, which all can be difficult to detect but yet result in significant decreases in load carrying capacity. The ability to monitor a structure in real time would increase safety, lead to a reduction of maintenance costs, both in terms of reduced downtime and easier repairs, and allow for reduced requirements in design loads. One of the most promising techniques for a structural health monitoring system is using Lamb waves since they have a great ability to propagate over large area and have good sensitivity and resolution. A number of carbon fiber FOGV, equipped with piezoelectric transducers, has been manufactured at GKN Aerospace Sweden AB. By using the piezoelectric transducers to send a wave pulses through the structures and compare the pulse response for a damaged and an undamaged case, it has been investigated if it is possible to detect damages, what the main limitations of the system are and if there are any possible improvements to be made. The piezoelectric elements ability to detect impacts has also been investigated. Most of the testing has been performed on a carbon fiber sandwich plate, to then apply the same principles for a FOGV. Lamb waves do indeed seem to have a great potential for detecting damages and a difference between the undamaged plate and the damaged plate could be observed both in the root mean square value, the peak-to-peak value, the time of flight and the frequency content of the pulse response. The piezoelectric sensors are very sensitive and have a great ability to detect impacts. The greatest limitations encountered during the project have been problems with the hardware, both with the amplifiers used and restrictions in data acquisition unit. Other limitations of the system are the sensitivity due to changes of boundary conditions and disturbances from external sources.
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BVD</td>
<td>Barely visible damage</td>
</tr>
<tr>
<td>CWT</td>
<td>Continuous wavelet transform</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>DWT</td>
<td>Discrete wavelet transform</td>
</tr>
<tr>
<td>FOGV</td>
<td>Fan outlet guide vane</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier transform</td>
</tr>
<tr>
<td>LL</td>
<td>Limit load</td>
</tr>
<tr>
<td>NDE</td>
<td>Non destructive evaluation</td>
</tr>
<tr>
<td>PWAS</td>
<td>Piezoelectric wafer active sensor</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>RTM</td>
<td>Resin transfer molding</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural health monitoring</td>
</tr>
<tr>
<td>STFT</td>
<td>Short time fourier transform</td>
</tr>
<tr>
<td>ToF</td>
<td>Time of flight</td>
</tr>
<tr>
<td>UL</td>
<td>Ultimate load</td>
</tr>
<tr>
<td>WT</td>
<td>Wavelet transform</td>
</tr>
</tbody>
</table>
1. Introduction

This master thesis work has been performed at GKN Aerospace Sweden AB in Trollhättan. This chapter gives an introduction to the purpose and the objectives of the master thesis and to the company GKN.

1.1 GKN Aerospace Sweden AB

GKN is a global company who operates in four different divisions; Aerospace, Driveline, Powder Metallurgy and Land System. The company has facilities in more than 30 countries and over 56 000 employees of which nearly 17 000 work within the aerospace division (GKN.com, 2016). The aerospace division is active both within military and the civil area, and about 75 % of the production and development are within the commercial market and the remaining 25 % within military applications (GKN.com, 2016). The facility in Trollhättan is part of the Aerospace division and belongs to the subdivision Engine System. Engine System, with its headquarter in Trollhättan, has facilities in four countries; Sweden, Norway, Mexico and USA (GKN.se, 2016). Not only manufacturing and design of commercial, military and space products are done at the facility in Trollhättan, but also engine service and maintenance.

1.2 Background

Structural Health Monitoring (SHM) is an area of growing interest and a lot of research has been conducted during the last decades (Bar-Cohen, 2000). The concept of SHM is especially interesting within the aerospace industry where the need to ensure the quality of a structure is particularly important. The performance of a structure is directly related to its health and thus in the end it comes down to safety (Staszewski, et al., 2004). Techniques and methods for non destructive evaluation (NDE) were established in the early 70’s and are a large part of the foundation in SHM (Bar-Cohen, 2000). Even if safety might be the most obvious argument to why SHM is beneficial, there are many others reasons as well. The cost of maintenance and repairs are approximately one quarter of the operating cost of a commercial aircraft and the number is increasing with an increasing age of the existing infrastructure (Giurgiutiu, 2008). The need of structural repairs entitles cost in two ways, the direct cost of the repair and the fact that the aircraft has to be taken out of service during the repair time. If it is possible to detect the damage in an earlier stage, fewer repairs are of course needed which both reduces the direct cost and the downtime of the aircraft (Staszewski, et al., 2004).

The use of composite structures in the aerospace industry is constantly growing and new applications are constantly being researched. This is mainly to their superior stiffness to weight ratio, but also due to their low electromagnetic reflectance and the ability to embed sensors and actuators (Bar-Cohen, 2000). New commercial aircrafts such as Boeing 787 and Airbus A350 XWB both have a composite content by weight of over 50% (Giurgiutiu, 2016). For the Boeing 787 this is equivalent with content by volume of 80%. The major application for fiber composites are the structural parts of the hull while the engine still are made of aluminum and titanium alloys. Leading engine manufacturers in the aviation industry today does however have example fan blades constructed out of fiber composite materials (ge aviation.com, 2015) (Rolls-Royce.com, 2015).

Even if composite structures have many advantages, they do indeed also have many disadvantages. The cost of maintaining them is for example considerably higher and the behavior of composites with
respect to fatigue and crack propagation is not as well known as it is with metal structures (Bar-Cohen, 2000). Metallic materials have been extensively studied for a long time and their material properties and fatigue behavior are very well known by now. For composites on the other hand, fatigue depends to a large amount on both the material parameters of the fibers and matrix, the layup sequence and manufacturing method and may thus vary from part to part (Giurgiutiu, 2016). Composite structures can also have internal or barely visible damages (BVD) that can be extremely difficult to detect, but still can have a huge influence on the mechanical properties of the structure, Table 1.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Effect on the material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination</td>
<td>Catastrophic failure due to loss of interlaminar shear carrying capability.</td>
</tr>
<tr>
<td>Impact damage</td>
<td>The effect on the compression static strength:</td>
</tr>
<tr>
<td></td>
<td>* Easily visible damage can cause 80% loss</td>
</tr>
<tr>
<td></td>
<td>* Barley visible damage can cause 65% loss</td>
</tr>
<tr>
<td>Ply gap</td>
<td>Degradation depends on stacking order and location</td>
</tr>
<tr>
<td></td>
<td>For [0,45,90,-45]_{2s} laminate:</td>
</tr>
<tr>
<td></td>
<td>* 9% strength reduction due to gap in 0(^\circ) ply</td>
</tr>
<tr>
<td></td>
<td>* 17% strength reduction due to gap in 90(^\circ) ply</td>
</tr>
<tr>
<td>Ply waviness</td>
<td>Strength loss can be predicted by assuming loss of load carrying capability</td>
</tr>
<tr>
<td></td>
<td>For 0(^\circ) ply waviness in [0,45,90,-45]_{s} laminate, static reduction is:</td>
</tr>
<tr>
<td></td>
<td>* 10% for slight waviness</td>
</tr>
<tr>
<td></td>
<td>* 25% for extreme waviness</td>
</tr>
<tr>
<td></td>
<td>Fatigue life is reduced at least by a factor of 10</td>
</tr>
<tr>
<td>Porosity</td>
<td>Degrades matrix dominated properties</td>
</tr>
<tr>
<td></td>
<td>* 1% porosity reduces strength by 5% and fatigue life by a factor of 2</td>
</tr>
<tr>
<td></td>
<td>* Increases equilibrium moisture level</td>
</tr>
<tr>
<td></td>
<td>* Aggravates thermal-spike phenomena</td>
</tr>
<tr>
<td>Surface notches</td>
<td>Static strength reduction of up to 50%</td>
</tr>
<tr>
<td></td>
<td>* Local delamination at notch</td>
</tr>
<tr>
<td>Thermal overexposure</td>
<td>Matrix cracking, delamination, fiber deboning and permanent reduction in</td>
</tr>
<tr>
<td></td>
<td>glass transition temperature</td>
</tr>
</tbody>
</table>

Although the uses of high performance composite materials have not grown as fast as predicted in the early 80’s, there has indeed been a continuous up going trend (Giurgiutiu, 2016). One of the reasons why the growth has been slower than predicted is the high cost of certification of new components and their relatively low resistance to impact. In spite of composites popularity in general and the great expectations for the future, there are many challenges to overcome, and most of them are related to safety. European Aviation Safety Agency (EASA) is the organization responsible for certification of civilian aircrafts in Europe. To get an aircraft certified it has to withstand certain criteria on the so called Limit Loads (LL) and Ultimate Loads (UL). The LL and UL are defined as the maximum loads to be expected in service and the LL multiplied by prescribed factor of safety (EASA, 2007). This means that a structure must:

- Be able to support limit loads without detrimental permanent deformation.
- Be able to support ultimate loads without failure.

---

If a SHM system would be implemented the requirements for the LL and the UL could be reduced quite significantly. For a system that can correctly detect damage within 50 flights a reduction of the LL is allowed with 15%. For an immediately detectable damage, where the crew can be directly informed about the danger, a reduction with 30% is allowed (EASA, 2007).

GKN has during the last couple of years developed a composite fan outlet guide vane (FOGV) for a commercial turbofan engine. A FOGV is a load bearing structure located behind the fan. Its purpose combine load bearing properties with great aerodynamic qualities to remove swirls in the air flow coming from the fan without reducing the pressure, Figure 1.

![Figure 1. Turbofan engine.](image)

Normally there are about 40 to 50 of these vanes in a long range turbo fan engine. In collaboration with ÅAC Microtec AB and Uppsala University, a couple of such vanes have been equipped with piezoelectric transducers, thermocouples and strain gauges, in a research project within the European framework program FP7, called E-Break. The project has been running for a few years, and the purpose of the FOGV study has been to obtain new knowledge about structural health monitoring and non destructive evaluation.

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2 Image from E-brake project report
1.3 Objectives

The objective of this master thesis work is to investigate the potential of the current system implemented in the FOGVs available at GKN. The duration of the project is 20 weeks and focus will be the usage and application areas for the piezoelectric transducer. The main aspects that will be investigated are:

- Can the system be used to detect and localize impacts?
- What is the potential of the system for detecting damage (cracks, micro-cracks, delimitation, surface notches, ply gaps and porosity)?
- What are the main limitations with the current system?
- What possible improvements are there to be made?
2. Literature Study

Initially a literature survey was done to provide an overview of the previous research conducted in the area. A dozen items was already available due to searches made earlier in the E-break project. These were a good foundation for identifying keywords and expanding the search. Common searches were Lamb waves, Lamb wave, Structural Health Monitoring, SHM, Ultrasonic, Piezoelectric, PWAS, Damage detection and combinations of these. Databases used were mainly Google scholar, KTH Primo and Scopus. The bulk of the literature search was done during the first half of the project but the work with the theoretical framework continued and was revised alongside the other work throughout the project.

Overall, its seems to be consensus that piezoelectric generated Lamb waves has great potential for SHM even though there is a lot of research still to be performed before a working system will be possible to implement for real use applications. Research have previously been performed both to investigate the effect of cracks, holes and delamination, mostly in plates and beam structures.

A source critical approach has been sustained during the entire literature survey. Although much of the basic facts have been taken from the two textbooks, Health monitoring of aerospace structures and Structural health monitoring with piezoelectric wafer active sensors, in most cases other independent sources have been used as validation. Because a large amount of new research is available on the area all of the literature was written after the year of 2000. Most sources are also peer reviewed and published, and there is no obvious reason to suspect that any tendency or bias would occur.
3. Theory

This section provides an overview of most general theories and methods considering SHM and a brief summary of the state of the art research will be presented.

3.1 Structural health monitoring

SHM can be divided into two categories, active and passive monitoring (Giurgiuțiu, 2008). Passive SHM can be used to examine the structure and measure various parameters to determine the health from the data. Passive SHM is useful but does not fully solve the problem since it does not examine the structure while in action. It can however have benefits during maintenance and reduce the down time and the cost. Active SHM on the other hand interacts with the structure to continuously monitor the health of the structure and detects eventual damage. How suitable a technique is depends on the resolution and sensitivity, the ability to distinguish closely spaced defects and the ability to detect small size damages, which varies with different techniques, but also of course how easy it is to implement the technique in the chosen structure (Díaz Valdés & Soutis, 2002). Both active and passive monitoring is essentially based on the same NDE principles, which are:

**Visual Inspection:** Visual inspection is the most common technique used for maintenance. It has some limitations regarding the type of damages possible to detect, but fatigue cracks and delaminations are possible to detect. Visual inspection does not require any sophisticated or expensive equipment, but illumination techniques are being developed and could thus improve the method. Microscopy can be used for identification of micro cracks and crack initiation, but often requires laboratory environment and is thus not suitable for aircraft maintenance since the part to be inspected has to be removed. It is over all a quite time consuming and inefficient process with limited accuracy. (Staszewski, et al., 2004)

**Ultrasonic Inspection:** The technique is based on the properties of the propagation of ultrasonic waves in different materials. By sending an ultrasonic pulse by either a probe or a piezoelectric element, damages can be detected by observing the scattering, reflection, frequency content, diffraction, harmonic generation, amplitude, wave mode and other physical phenomena. The techniques is often referred to as A-, B-, and C-scanning, where A-scanning is a point measurement with an ultrasonic wave going directly through the material and reflecting on the bottom surface and eventual damages. B-scanning measures along a single line, and C-scanning is a combination of B-scans to form a surface couture plot. The technique is well understood and has good sensitivity. It also entitles the possibility to locate the damage and is possible to use during flight. The resolution can however be limiting and the wave propagation is sensitive to the geometry of the structure. (Staszewski, et al., 2004)

**Eddy Current:** Eddy current is the third most common used technique for aircraft maintenance. A coil with a sinusoidal alternation current is used to induce closed loop of current in the material to be monitored. The closed loop (the Eddy current) is affected and distorted due to material defects. The method is suitable to detect strains and cracks in short specimens and around holes. It is a relatively cheap method and has good sensitivity. Eddy current can however be used on metal structures and is not
suitable for internal defects due to its poor penetration properties (max 6 mm). It also requires skills to operate and calibrate the equipment. (Staszewski, et al., 2004)

**Acoustic Emission:** When a solid material undergoes irreversible internal changes such as cracking, plastic deformation, fiber fracture, fiber deboning or delamination elastic energy is released. The release of acoustic emission can be registered using special accelerometers, piezoelectrics sensors or microphones. NDE with acoustic emission is well established and understood and have been successfully used for monitoring in many areas. By using triangulation damages can be localized. The sensitivity is however relatively low and measurements can’t be reproduced. (Staszewski, et al., 2004)

**Radiography, Thermography and Shearography:** Radiography uses gamma x-rays to scan the material, thermography uses the thermal conductivity and shearography creates an image of the shear stresses in the material. All of these methods have the advantage that they can quickly create an overview of large structures. However, the techniques are expensive and not as well-established and understood as the more common techniques. Sensitivity is also somewhat limited (Staszewski, et al., 2004)

Even if many of these techniques are widely used and understood most of them are not suitable for implementation, especially not if the idea is to be able to monitor the structure in service since they require a human operation of the equipment (Díaz Valdés & Soutis, 2002). For a SHM system to be fruitful it also has to fulfill other basic requirements such as:

**Weight:** The weight of the SHM system shall not be greater than justified by its benefits. For instance when the SHM system enables a structural weight reduction, the SHM system weight shall not be greater than the reduction. (Wallman, et al., 2013)

**Size and installation:** The size of the SHM system shall be small enough to be integrated in a structure without need to change the specified maximum envelope of the structure. (Wallman, et al., 2013)

**Temperature:** The SHM system shall withstand the engine structure temperature at its mounting position during the structure’s lifetime. Without the functionality of the SHM system can be degraded. (Wallman, et al., 2013)

**Storage:** The SHM equipment has to sustain the same storage environment as the monitored structure. (Wallman, et al., 2013)

**Lifespan:** The average life of the SHM system shall not be less than the average life of the monitored structure. (Wallman, et al., 2013)

**Reliability:** The service provided by the SHM system shall be reliable throughout the structure’s lifetime. Logged data shall comply with defined accuracy measures and alerts/alarms shall be provided as intended. (Wallman, et al., 2013)

**Cost:** The cost of the SHM system should be justifiable from a life cycle cost perspective. Non-recurring costs, installation and service costs should be low compared to the cost savings that the SHM system brings. (Wallman, et al., 2013)
**Maintenance**: SHM components and sensors must be possible to change during maintenance. (Wallman, et al., 2013)

Besides this, electronic components have to fulfill the conditions of the RTCA DO-160 standard regarding altitude, humidity, vibrations, waterproofness, sand and dust, magnetic effects, power input, voltage spikes, emission of radio frequency energy, lightning induced transient susceptibility, lightning direct effect, etc (Eurocae, 2010).

In a study of a sandwich beam with piezoelectric actuators in different configurations the effect of deboning was studied (Mustapha, et al., 2011). It was concluded that the location of the damage could be determined and the energy of the wave signal and the time of flight (ToF) was affected of the deboning and a correlation with the size of the damage could be seen, even though it was not possible to deduct a unique relation. Another study have shown that critical damage size in CFRP beams and sandwich structures can be successfully detected and located with low frequency (15 and 20 kHz) A₀ mode (Diamanti, et al., 2005). The conclusion was however also that, for the mentioned frequencies, the resolution was poor, and it was not possible to distinguish closely spaced damages. An interesting study looked at the influence from external vibrations in the frequency range between 10 Hz up to 100 Hz (Li, et al., 2015). Comparisons were carried out between the resulting Lamb wave signals from the vibrating plate for different boundary conditions and it could be shown that the external vibration did not influence the ToF during the application of Lamb wave based SHM but the received signal can be shifted or rotated due to the external vibrations since they will generate flexural waves in addition to the Lamb waves. Inspection of CFRP laminates has also been performed with promising results using an excitation frequency of <100 kHz (Díaz Valdés & Soutis, 2002). In this study a composite beam equipped with PWAS were used to detect delamination. Two interesting conclusions from this study were that due to the very minimalistic signal processing needed makes the technique suitable for real time in situ monitoring. It was also shown that even though the wavelength was 42 mm deboning of 10 mm i.e. only 25% of the wavelength could be detected. A review of the most representative studies in the area since 1990’s concluded that Lamb waves has an excellent propagation capability, high sensitivity to damage and are convenient with respect to generation and collection (Su, et al., 2006). It is important to carefully consider the excitation frequency, waveform, cycle number and other signal characteristics. It is also important to know that undesired modes only can be suppressed and not completely canceled out, which can generate complex wave patterns.

### 3.2 Piezoelectric Wafer Active Sensors and Lamb Waves

Lamb waves are the most widely used form of guided waves for structural damage detection (Staszewski, et al., 2004). Lamb waves can exist in thin plates with parallel free surfaces and are very effective for detecting cracks in thin sheet materials. Lamb waves are suitable for damage detection because they can travel over large distances in many types of materials. The waves can be initiated in several different ways, for example with laser, piezoelectric elements or ultrasonic probes (Su, et al., 2006). Piezoelectric wafer active sensors (PWAS) are very promising technique since it is cheap and can relatively easily be integrated in structures but also surface mounted on already existing structures (Giurgiutiu, 2008). Piezoelectric elements transform mechanical deformation to electric voltage but they can also be used the other way around, i.e. transforming electric voltage in to mechanical action. These properties makes PWAS great for generation and detection of Lamb waves and this dual application area impart the “active sensor” characteristics (Giurgiutiu, et al., 2003). When elastic waves propagate in thin materials with free boundary conditions all of the waves energy remains
contained within the plate, and Lamb waves are therefore also commonly referred to as “guided waves” (Giurgiutiu, et al., 2003). Another property of Lamb waves is that the particle displacement occurs both along the plane and across the thickness. Even if Lamb waves have great potential for damage detection and SHM, both regarding sensitivity and resolution, they do however have a highly dispersive behavior which can be very complex (Su, et al., 2006). An additional complicating factor is that Lamb waves can consist of both symmetric and asymmetric modes, Figure 2.

![Figure 2. Lamb waves, symmetric and asymmetric modes.](image)

Which modes are excited depend on the plate thickness and the frequency. The different modes are referred to as $S_m$ and $A_m$ and each mode has its own propagation velocity. Figure 3 shows the typical appearance of the propagation velocity for the different modes dependent of the product frequency and plate thickness. At higher frequencies and thicker plates a larger amount of modes are excited and thus generate even more complex wave distribution. It is therefore desirable to only excite the first $S_0$ and $A_0$ modes. The $A_0$ mode has a shorter wavelength and is more sensitive to damages and has better resolution, but it also has a more dispersive behavior than the $S_0$ mode at same frequencies and thus larger energy loss (Lu, et al., 2008). The $S_0$ mode on the other hand is simpler and the stresses occurring are almost uniform throughout the plate thickness, which indicates that this mode is equally sensitive to internal defects as it is to superficial defects (Lu, et al., 2008). It has also been proved that the $S_0$ mode provides much better reflections from cracks than the $A_0$ mode (Giurgiutiu, et al., 2003). To get reflections from damages the excitation frequency needs to be in the range hundreds of kilohertz to avoid the reflections superimposing with the transmitted pulse (ibid.).

---

The main factors influencing the propagation of a Lamb wave is of course the frequency and the plate thickness. The different modes can be described by solving:

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(k^2 - q^2)^2}
\]  

(1)

for symmetric modes, and:

\[
\frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2 - q^2)^2}{4k^2pq}
\]

(2)

for asymmetric modes. The parameters \( p, q \) and \( k \) can be calculated according to:

\[
p^2 = \frac{\omega^2}{c_L^2} - k^2
\]

(3)

\[
q^2 = \frac{\omega^2}{c_T^2} - k^2
\]

(4)

\[
k = \frac{\omega}{c_p}
\]

(5)

where \( h \) is the plate thickness, \( k \) is the wave number, \( c_L \) and \( c_T \) is the longitudinal respectively transverse mode velocities, \( c_p \) is the phase velocity and \( \omega \) is the circular frequency. By considering these equations it can be seen that the propagation velocity is dependent of the frequency regardless of mode. It can also easily be understood that anisotropic materials such as composites will obtain some interesting properties, such as direction-dependent speed, difference between phase and group velocities (Su, et al., 2006).

---

The task of selecting modes are difficult and in many cases it is not even possible to fully eliminate unwanted modes, it is however possible to reduce the amplitude of the undesired modes having only one mode dominating the contents of the wave (Su, et al., 2006).

It has also been examined how the PWAS size affects both the ability to send and receive wave pulses (Raghavan & Cesnik, 2004). The conclusion here was that the sensor should be as small as possible to maximize the magnitude of the response. The optimal length for an actuator is half the wavelength of the traveling wave, and the power consumption, $P$, is directly proportional to the actuator length, $a$, namely:

$$P \propto 2a$$  \hspace{1cm} (6)

### 3.3 Signal Processing

Signal processing is a crucial part of SHM, and a number of different approaches exist to identify and extract relevant features. Due to the extent of the area regarding signal processing, only the most general methods and ideas are treated in this report. Signal processing consists of a lot of different aspects, but roughly it can be divided into the main parts; data pre-processing, pattern recognition, filtering, time-domain analysis, frequency analysis, wavelet analysis and spectral analysis (Staszewski, et al., 2004). Signal processing within SHM is built at the following process (Giurgiutiu, 2008). A sensor transforms a physical state to digital data. The signal is pre-processed and disturbances and noise that corrupts the signal is removed. Relevant features for classification of the structure are extracted and patterns can be recognized in the extracted data making it possible to determine the state of the structure.

Since the noise can corrupt the information it is often reduced either by local or by global averaging or by filtering (Staszewski, et al., 2004). There are four classical filters functions, with different characteristics; Chebyshev I, Chebyshev II, Butterworth and Elliptic, Table 2.

**Table 2. Properties of the four filter functions.**

<table>
<thead>
<tr>
<th>Filter Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheby1</td>
<td>Have equi-ripples in the pass-band and monotonic in the stop-band. Rolls of faster than type 2, but at the expense of grater deviation from unity in pass-band.</td>
</tr>
<tr>
<td>Cheby2</td>
<td>Monotonic in the pass-band and equi-ripple in stop-band. Type 2 does not roll of as fast as type 1 but is free of pass-band ripple</td>
</tr>
<tr>
<td>Butter</td>
<td>Characterized by magnitude response that is maximally flat in the pass-band and monotonic overall</td>
</tr>
<tr>
<td>Ellip</td>
<td>Steeper roll off than Cheby and Butter but is equi-ripple in both pass- and stop-bands. Can meet given specification with lowest filter order of any type</td>
</tr>
</tbody>
</table>

The most common filters are; high-pass and low-pass, band-pass, band-stop, (Giurgiutiu, 2008). These four filter types have frequency responses according to Figure 4.

![Filter Types](https://en.wikipedia.org/wiki/Filter_%28signal_processing%29)

**Figure 4. Frequency response for low-pass, high-pass, band-pass and band-stop filters.**

Analysis in the time domain includes features such as the maximum amplitude value, the minimum amplitude value, peak-to-peak value and Root Mean Square (RMS) (Staszewski, et al., 2004). The RMS value is often used to give an indicator about the average energy of the signal and is defined as:

$$x_{RMS} = \sqrt{\frac{1}{T} \int_0^T x^2(t) dt}$$  \hspace{1cm} (7)

where $T$ is the duration of the signal and $x(t)$ is the amplitude of the signal at time $t$. The statistical moments are also commonly used to obtain information about a signal (Staszewski, et al., 2004). The first and the second statistical moments are the average and the variance. The fourth normalized moment is called the Kurtosis (and describe “the spikiness” of the signal) (Staszewski, et al., 2004).

The classical Fourier transform (FT) is used transform a signal from the time domain to the frequency domain and the inverse Fourier transform ($\text{FT}^{-1}$) is of course used to transformer back from frequency domain to time domain. The FT is defined as:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt$$  \hspace{1cm} (8)

where $\omega$ is the angular frequency and $j$ is the imaginary unit, $X(\omega)$ is the Fourier transform of $x(t)$.

This allows examining the frequency content of a given signal. (Staszewski, et al., 2004) A problem with this approached however is that the frequency content in a signal changes in most cases as the time goes by. The short-time Fourier transform (STFT) can thus be used to create a spectrogram, giving the frequency spectra for different segments of the time signal. (Giurgiutiu, 2008) The STFT is basically the same as the classic FT but instead of doing an analysis of the entire signal a time window is moved over the signal thus giving a more complete picture of how frequency content change during the duration time. The quality of the spectrogram will depend on window size, the step length for the moving window and the type of window used. If for example a very short time window is used, it will require a larger amount of low frequencies which gives an inaccurate representation of the signal, if on the other hand a too large window is used the signal will not be correctly revealed. A too large step moving size will generate discontinues in the spectrogram and poor resolution. In other words, there will be a tradeoff between time and frequency resolution using the STFT. (Giurgiutiu, 2008). The fast Fourier transform (FFT) is an efficient algorithm for calculating discrete limited FT. Calculating the

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FT of a discrete signal normally requires $N^2$ multiplications, while a FFT reduces the number to $N \log N$ thus entitling less calculating capacity.

Another type of transform that is becoming more and more used is the wavelet transform (WT). It reminds a lot of the FT, but instead of building the signal of an infinite number of sines and cosines of different frequencies, it uses a functional basis consisting of dilated and shifted versions of a “mother wavelet”. (Giurgiutiu, 2008) The two most common used types of wavelet transform are the continuous wavelet transform (CWT) and the discrete wavelet transforms (DWT). The CWT is extensively used for time-frequency analysis and is generally used for Lamb wave signals. The DWT is used for image compression, filtration, de-noising and feature extraction (Su, et al., 2006).

The CWT can be expressed as:

$$W_{\psi}(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^*(\frac{t-b}{a}) \, dt.$$  \tag{9}

In this case, $b$ is a translation indicating the time locality, $a$ is the dilation or scale parameter, $\psi(t)$ is the mother wavelet and $\psi^*$ is its complex conjugate (Staszewski, et al., 2004). The normalization with $1/\sqrt{a}$ ensures the integrated energy given by each wavelet is independent of the dilation $a$. One of the most widely used mother wavelets in the continuous analysis is the Morlet wavelet (Staszewski, et al., 2004), which is defined as:

$$\psi(t) = e^{j \omega_0 t} e^{-|t|^2/2}. \tag{10}$$

To compare wavelet transformations there are two factors that are extra important. The smoothness and the compact support of the wavelet function. The smoothness of a function corresponds to the decay of its Fourier transform and the support of the function means the smallest closed set outside which the function vanishes identically (Staszewski, et al., 2004).

### 3.4 System Identification

Just like signal processing is system identificationa complex area that would require several books to cover completely. The idea of system identification is to identify a model that can describe the properties of a system given the input and output data. Basically there are four different areas within system theory; modeling, analysis, estimation and control (Keesman, 2011). The first step is to create a model that can describe the physical relation between the input signal, $u$, and the output, $y$, in an adequate way, prior knowledge about the system, assumptions made and uncertainties have to be taken into consideration. For SHM this is the most important step together with analysis. Control theory on the other hand, where system identification also is an important part, requires a different approach. Where estimations and control are equally important, and characteristics such as stability, sensitivity and observability are of greater focus. Models are often divided into different classes depending on how the model has been accomplished.

**White box model:** A white box model is based on physical laws, describing the relationship between properties for relevant variables. By implementing this in a software support and organize them suitably, a model of the system can be achieved. It is however very rare to know all relevant the physical qualities in a system, and even if they are known a white box model is often very complex and in most cases not suitable. (Keesman, 2011)
**Black box model:** A black box model does not take the underlying physical phenomena into consideration at all, but just tries to find a sufficient description between the output and the input. A black box model is in many cases sufficient and is the most commonly used type of algorithm in system identification applications. (Keesman, 2011)

**Grey box model:** There are a large number of shades of grey models, depending on how much of the model is based on known physical properties. If a few of the physical relations between output and input are unknown or uncertain realistic predictions have to be obtained. Grey models exist in the entire spectra from almost white, meaning there is just some parameter having an unknown numerical value, to almost entirely black models, having almost entirely back flexible building blocks and physical insights. (Ljung, 2010)
4. Hardware and Equipment Setup

One plate and three FOGVs were manufactured by GKN Aerospace Applied Composites AB (ACAB) in Linköping. The manufacturing was done with resin transfer molding (RTM) and the skin was a carbon fiber/epoxy laminate. The plate is a single skin laminate with a face thickness of 4 mm, and core thickness of 15 mm. The length and width of the plate were 775x75 mm. The FOGV is also a sandwich structure, though with a slightly thicker composite laminate and a much heavier foam core. Material data for the FOGVs are presented in Table 3.

Table 3. Material data for the FOGV

<table>
<thead>
<tr>
<th></th>
<th>Core</th>
<th>Laminate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>203</td>
<td>1525</td>
</tr>
<tr>
<td>Shear modulus [MPa]</td>
<td>134.5</td>
<td>-</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>-</td>
<td>46.2e³/11.6e³</td>
</tr>
<tr>
<td>(in plane/out of plane) [MPa]</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Poissons ratio</td>
<td>-</td>
<td>0.32/0.085</td>
</tr>
<tr>
<td>(in plane/out of plane)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

The FOGVs are not only equipped with piezoelectric transducers, but also with thermocouples and strain gauges. The plate on the other hand is only equipped with PWAS. The thermocouples and the strain gauges have been tested briefly in previous parts of the E-Break project but will not be examined in any way in this master’s thesis.

The data acquisition has been done with a National Instrument Data Acquisition unit (DAQ), the DAQ has also been used for generating and sending the pulse to the PWAS, though with help from an amplifier. Two different amplifiers have been used during the project, both having an amplification of 50 times the original signal. The first amplifier was connected to a power supply which had been slightly modified with an extra capacitor to prevent transients in the output signal. It was however discovered halfway through the project that a more powerful amplifier was needed to be able to send pulses of high enough voltage and frequencies without obtaining a corrupt signal, more about this in section 6.1. For a more detailed description of the connection setup see Appendix A.

There were some limitations in the DAQ device which had do be considered during the testing, these were:

- Maximum sampling rate for the input: 1 MS/s.
- Maximum sampling rate for the output: 2.86 MS/s.
- Maximum voltage: ±10 V.
- Maximum current for the output signal with amplifier 2: 0.25 A

There are two different versions of PWAS used, both in the FOGVs and the plate. A smaller version, thought to detect vibrations and waves in the composite skin, and one larger version, which mainly is thought to be used as the transmitter. The specifications for the two types are given in Table 4.
Table 4. Specifications for the piezoelectric elements.

<table>
<thead>
<tr>
<th></th>
<th>Large version</th>
<th>Small version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>P-876.A11</td>
<td>P-876.SP1</td>
</tr>
<tr>
<td>Capacitance [nF]</td>
<td>150</td>
<td>4.75</td>
</tr>
<tr>
<td>Operating Voltage [V]</td>
<td>-50 to 200</td>
<td>-100 to 400</td>
</tr>
<tr>
<td>Dimensions [mm]</td>
<td>61x35x0.4</td>
<td>16x13x0.5</td>
</tr>
</tbody>
</table>

The plate is equipped with three larger PWAS and one of the small PWAS. The placement of the transducers is shown in Figure 5.

![Figure 5. Schematic sketch of the instrumented test plate, side view.](image)

The FOGV has two small sensors and one of the larger. In the FOGV all of the PWAS were placed between the core and the laminate, just as T1 and T4 shown in Figure 5.

The FOGV is equipped with two small piezoelectric sensors, S1 and S2, and a large element used as an actuator A1, located as seen in Figure 6. The laminate is a RTM-manufactured carbon fiber laminate with a thickness of approximately 4 mm.

![Figure 6. Schematic sketch of the instrumentation of the FOGV core.](image)

The distance between PZT’s A1 and S1 and sensor S2 is approximately 50 cm. The core has a thickness of about 1 cm at its thickest and is approximately 21 cm wide.
5. Experimental Work

The following chapter describes the work performed, the tests conducted and the purpose of the tests. In general the work can be divided in to four subparts, SHM by sending pulses though the carbon fiber plate, SHM by sending pulses though the FOGV, monitoring the plate during impact and monitoring the FOGV during impact.

5.1 Sending Pulses and Detecting Impact

The first part of the project focuses on the plate to create an understanding of the piezoelectric elements and the propagation of Lamb waves. The focus is also to generate functional LabVIEW programs for generating and reading pulses and another program for monitoring the plate during impacts. When functional programs are obtained the idea is to characterize the plate properties. This was done by sending pulses though the plate with different frequencies and amplitudes. Both a symmetric pulse and an asymmetric pulse are used to allow comparison later and to see if the type of pulse influences the pulse response. The two different types of pulses are generated as:

\[ S(t) = a \cos(\omega t) \cdot \sin^2 \left( \frac{\omega t}{10} \right) \]  
\[ A(t) = a \sin(\omega t) \cdot \sin^2 \left( \frac{\omega t}{10} \right) \]

where \( a \), is the amplitude, \( \omega \) the circular frequency and \( t \) the time. \( S(t) \) and \( A(t) \) are the symmetric and asymmetric pulse, Figure 7 and Figure 8.

![Waveform Graph](image)

Figure 7. Symmetric pulse generated in LabVIEW with equation (11).
Asymmetric pulse generated in LabVIEW with equation (12).

The plate was used in the first part of the project to verify that the LabVIEW program that could send and receive pulses in an efficient way. Many different variants with different sampling frequencies for reading and writing data and for generating the pulse, were tested before a sufficient results was achieved. The block diagrams generated are shown and explained in Appendix B. A LabVIEW program for detecting impacts and save data were also created, see Appendix C. The numbers of samples in one sent pulse was calculated as:

\[ N_s = \frac{nS}{\omega} \]  

where \( n \) is the number of periods in the pulse, \( S \) the sample rate for the DAQ device and \( \omega \) the frequency. For the wave pulse sent, \( n = 5 \), and the sample rate \( S \). In the beginning \( S \) was set to 1 MS/s, but was later changed to 2 MS/s, to get a larger number of samples in the higher frequency range. For measuring the signal the default setting was chosen to 500 kS/s regardless of if the acquisition were made with one or two sensors, this was to facilitate the handling of the data later on in the project. When two input signals and the output signal had to be measured, the sampling rate was lowered to 333.333 kS/s, which was considered to be sufficient. This value was chosen because of the mentioned limitations in sampling frequency in the DAQ.

The frequency range used went from 1 000 to 30 000 Hz with an interval of 1 000 Hz. The decision to not go past 30 kHz was made partly because of limitations with the hardware and partly arbitrarily to delimit the project. If it would be possible to detect damages in this frequency range, less advanced hardware and energy is required than using an excitation frequency of for instance 300 – 600 kHz. Different amplitudes of the output signal generated with the DAQ unit were tested for both symmetric and asymmetric pulses. Both the sent pulse and the pulse response were measured and the data was then used to perform a number of different analyses, both in the time and frequency domain. The main properties compared were; energy content of the signal, peak-to-peak value and frequency content. When performing the test of sending and receiving pulses the transducer T1 was used as the transmitter and T4 was used as the sensor. The reason for this was to get as similar conditions as possible as to those used in the FOGV where a large PWAS is used as a transmitter and a small PWAS is used as the receiver. The transducers T1 and T4 are also placed between the skin and the core in a similar way as in the FOGV unlike the transducers T2 and T3. When performing the impact test however T2 and T3 were used. In this case it was important to have PWAS of the same size and also to have them located on the same side of the laminate to get as similar conditions as possible.
The LabVIEW programs created were slightly modified to be used for the FOGV. For the program using to send and receive pulses, the sampling frequency was changed from 500 kHz to 333.333 kHz. This was, as mentioned, done to be able to take measurements from both the S1 and S2 sensor and capture the sent pulse. The sent pulse was used to organize the data and place the different measurements on the same time scale to allow comparisons, the same was of course true for the plate. Since the FOGV were much stiffer the amplitude had to be increased from 0.25 V to 0.6 V. And as mentioned this was a problem with the DAQ unit. This was solved by adding an extra output for the DAQ connected in parallel to the amplifier, this also created the need to modify the LabVIEW block diagram, Appendix B. For the impact the trigger level was changed from 1 V to 0.2 V and the number of samples saved was increased from 5 000 to 10 000.

By knocking at the plate near one of the sensors, an approximation of the propagation velocity of the waves in the plate could be obtained by simply comparing the time difference between the response of the first sensor and the second sensor. Instead of manually tapping or knocking at the plate, a small glass ball was dropped on the plate through a tube. This refinement was also implemented after the impact test, meaning the plate already having two damages to take in to consideration in the reference data. On the other hand, it made it possible to compare how the waves looked and behaved depending on whether or not the waves had to travel through one, two or no damage before being registered by the sensor. The impact where done at three different places, 10 cm from center of sensor T2, in the middle of the plate and 10 cm from the center of sensor T3 (Figure 9). The wave propagation velocity was also attempted to be estimated by looking at the time domain signal for the sent pulses. Since both the transmitted and the received pulse were measured and the distance between T1 and T4 are known. Comparisons of the frequency content of the impact both before and after damage could then be made.

![Figure 9. Schematic sketch of the plate, top view, where the circles 11 and 22 represent the damaged areas from the impact test, the X symbolizes the places where the ball where dropped.](image)

### 5.2 Damage Created

A destructive test was performed at the Royal Institute of Technology (KTH) in Stockholm, where a calibrated impact rig was available. The goal was to create a BVD and then do the same measurements again. The impact test was an ordinary impact test, where an impactor with a weight of 3.04 kg and a diameter of 16 mm, was dropped from a certain height. Depending on the height the impact energy varied according to:

$$E = mgh$$  \hspace{1cm} (14)

where $m$ is the mass of the impactor, $h$ is the height, and $g$ is the gravitation. From similar tests preformed (Diamanti, et al., 2005), though on thinner plates, BVD was detected in sandwich composite beams with flange layup and energy levels according to: $[0]_8 - 2 J$, $[90]_{16} - 2 J$, $[+45/45]_{18} - 10 J$ and $[+45/0/-45/90]_{28} - 4 J$. From pervious test performed at KTH on RTM manufactured carbon
fiber composites plates with different thickness, the energy level for BVD had been determined to: 2 mm – 10 J, 3 mm – 17 J, 4 mm – 22 J and 5 mm – 30 J.

A relation between material properties, skin thickness and impact force for BVD can also be described as (Abrate, 1998):

\[ P^2 = \frac{8\pi^2 Eh^3}{9(1 - \nu^2)} G_{IIc} \]  
(15)

Where \( P \) is the impact force, \( E \) is young’s modulus, \( h \) is the thickness, \( \nu \) is Poisson’s ratio and \( G_{IIc} \) is a critical value for when delamination occurs. For carbon fiber epoxy \( G_{IIc} = 0.8 \text{ N/mm} \). A quick estimation with this formula gives an impact force of approximately 152 N. Assuming an impactor weight of 3 kg, a height of 0.75 m, a duration of the impulse of 0.1 s and 10% conservation of impact energy, this would, calculated with equation (15), correspond to 126.5 N. This gives a very rough estimate of the drop height.

To ensure that the impact energy was of the right magnitude, an extra plate (without instrumentation) was used as a test plate. The test plate did however have a laminate thickness of 6 mm compared to the instrumented plate which had a laminate thickness of 4 mm. Impacts from different heights, 0.2, 0.5 and 1.0 m was done on the test plate which, calculated with equation (14), correspond to the energy levels 5.96 J, 15.90 J and 29.79 J. After the drop test an ultrasonic A-scanning was be performed to get an indication of the size of the caused damage. Two impacts were then performed on the instrumented plate, from the heights 0.4 and 1.0 m and for the instrumented plate 11.92 J and 29.79 J. Between the impacts a A-scan was done on the instrumented plate. Measurements of the piezoelectric elements were made also by sending pulses in the manner described above. The reason for doing two impacts was to be able to compare an undamaged plate, a plate with a BVD and a plate with an easy visible damage.

Unfortunately it turned out on closer investigation, that the boundary conditions for the plate had far greater influence than originally thought. This combined with the problems with the amplifier (which also was identified after the impact tests where preformed) made it very difficult to obtain any useful results from these measurements, more about this in section Results and Discussion. This meant that the method had to be revised slightly, and the damaged plate had to be used as the reference. To solve this problem a new amplifier was purchased that would be able to transmit a sufficient frequency and amplitude. Since there only was one instrumented plate to use and there were no possibilities to manufacture a new one, the plate used as reference now already had two damages, and this would have to be considered while analyzing the results. A new damage was now instead done by drilling a hole with the diameter 6 mm. The hole was drilled where the larger of the two impacts was done. The idea of this was to not introduce an additional damage that would influence the measured signal, but rather to create damage that had larger influence than the two impact damages. All of the results is comparison between the plate after the impact and the holes. When referring to “undamaged plate”, it is the plate with the two impact damages intended. The “damaged plate” and “the damage” are referring to the plate with the hole and the hole respectively.

The hole was then enlarged to 8.7 mm to see how a “larger” damage of the same type would affect the wave propagation, frequencies and the energy content. Measurements were taken again in the same way as earlier, from 1 kHz to 30 kHz with an interval of 1 kHz. And once again the RMS value, the peak-to-peak value and the frequency was compared. The reason for making the hole larger instead of drilling a second hole, which also was considered, was the thought that it would be more interesting to
see how a larger damage of the same type in the same location would affect the result instead of creating a second damage that would complicate the propagation pattern. In an actual application the likelihood that damage grows from an existing incipient damage is significantly more probable than that another similar damage would occur in a different place, even though a hole is not a very realistic type of damage.

No form of damage was created in the FOGV, but reference measurements were done to ensure the same methods used on the plate were applicable. The same frequency interval, 1 – 30 kHz, was used. The impact test was not as carefully carried out on the FOGV as on the plate since the results from the plate indicated this was not a useful method. The main focus of the impact test performed on the FOGV was to see if the S1 and S2 sensor behaved in a similar way or if obvious differences could be observed.

5.3 Handling of Data

After the damage the idea was as mentioned to analyze and compare the measured data from the damaged and the intact plate. This was done using MATLAB. The RMS value for the signals was calculated with the MATLAB command `rms(x)` which calculates the RMS value according to equation (7). The peak-to-peak value was calculated with the command `p2p(x)`, and frequency spectra’s of the signals was calculated with the command `fft(x)`.

A problem with the DAQ unit was that when measuring the sent pulse some overhearing occurred between the different channels. This could be detected by connecting the plate to the DAQ as if a measurement should be done, but without connecting the amplifier to the transmitter. By measuring the overhearing for all the frequencies (1-30 kHz) and applying a high pass filter with cut of frequency 800 Hz to the measured data, a good representation of the “false signal” was obtained and could simply be subtracted from the test data to receive the “real signals”. The same principle was used at the data from the FOGV

At first it was also meant to investigate the possibility to observe reflections from the damages and to make an attempt to create a black box model of the system with the MATLAB system identification toolbox, both of the damaged and the undamaged plate. The black box model was supposed to be compared before and after the damage to withdraw differences of the two models to see if this would be a suitable way of detecting damages. It was also thought that if the data from the undamaged plate would be implemented in the model for the damaged plate, the model would provide a lower fit than the model for the intact plate. An attempt was also made to perform a wavelet analysis using the MATLAB wavelet toolbox. The idea with this was mainly to see if any additional interesting could be obtained. The wavelet analyze was performed with the MATLAB command `cwt(x)` calculates a CWT as described in equation (9), a Morlet wavelet, equation (10), was used as the mother wavelet.
6. Results

In this section obtained results will be presented. First the results obtained from the tests on the plate will be presented followed by the results obtained from investigating the FOGV.

6.1 Plate

One of the first things tested was different connection of the PWAS to the DAQ device where it was noticed that if the PWAS was connected to + and - instead of + and GDN a much better signal was obtained with less noise and a significantly smaller influence of the 50 Hz frequency (Figure 10). The connection + to – was thus the only one used in the further testing.

![Figure 10. Comparison of pulse response between + to – connection and + to GND connection](image)

The frequency of the sent pulse made a large difference in the measured response. By comparing the peak-to-peak value (Figure 11), the RMS value (Figure 12) and by looking at the signal for different excitation frequencies in the time and frequency domain, Appendix D and Appendix E, it could be concluded that a frequency of 6-8 kHz was best preserved though the plate and gave much larger amplitude in the response signal. This did of course not mean that this would be the frequencies best suitable for damage detection. A first assumption was however made that a change of the plate’s properties due to damage would have a notable influence at these frequencies since if the damage in some way changes the eigen frequencies of the plate, this would be where it was most detectable.
As mentioned both symmetric and asymmetric pulses were tested to compare if there would be any different in the energy or frequency content of the two. No significant difference could be detected between the two cases, nor could any obvious difference be observed in the time domain (Figure 13 and Figure 14), of the pulse response. For the 20 symmetric pulses considered in this comparison the RMS value varied between $1.067 \times 10^{-2}$ and $1.084 \times 10^{-2}$ V and for the asymmetric pulse the RMS value had a minimum of $1.063 \times 10^{-2}$ and a maximum of $1.072 \times 10^{-2}$ V.
The amplitude also had an impact on how good the pulse response would turn out. This did however have more to do with the limitations of the amplifier and the DAQ than the properties of the plate. A pulse sent with a higher amplitude did of course entitle a response signal with higher amplitude as well, but as long as the measured signal was well distinguishable from the noise the amplitude seemed to be of lesser importance in that regard. The problem with different amplitudes did instead depend on the amplifier used. The first amplifier used had a problem discharging fast enough which for frequencies over about 8 kHz and amplitudes over 1.0 V resulted in a superimposed pulse. For lower
amplitudes fairly good, but slightly deformed, pulses could be generated for frequencies up to about 18 kHz. When the second amplifier was used a very nice pulse response could be obtained with amplitude from the DAQ unit of 0.25V. For higher amplitudes did the DAQ unit had troubles delivering enough current which caused the output signal to become saturated (Figure 15). This did however not seem to be a problem while investigating the plate but did cause some issues while working with the FOGV.

![Figure 15. Sent pulse of amplitude ±1 V.](image)

The overhearing in the DAQ seemed to be most notable from the channels with the lower number to the higher, e.i. the signal leaked from channel ai1 to ai2 to ai3 and so on. To minimize the overhearing the signal with largest amplitude (the sent pulse) was thus connected to the port with the highest number (ai7).

The variation of the different boundary conditions of the plate turned out to have a huge impact of how the response would turn out. Even very small differences such as the plate lying on a cable or the foam core being in contact with something else than the table would completely change the received pulse. Due to the boundary conditions of the plate having a much larger influence than first noticed in combination with the amplifier not generating an outputs as good as first thought the data from the impact test was of limited value.

The idea of monitoring the plate while knocking or dropping a small weight (in this case a glass ball) on it to see if the frequency content of such a knock would change before and after the damage did not appear to have any success. A much larger differences were observed between the two sensors (Figure 16), than what could be observed between the measurements before and after a hole had been drilled,. The measured signals in a sensor did also vary a lot due to where the impact occurred. A few millimeters closer to or further away from the sensor would make a larger difference in the output signal than the drilled hole would have (Figure 17 - Figure 19).
Figure 16. Comparison between T2 and T3 during impact.

Figure 17. PSD spectra of measured signal in T2 and T3 for the damaged and undamaged plate.
Knocking on the plate while taking measurements with sensors in both ends was however a good way to measure the ToF. With an impact at the mark between the locations T2 and 11, it was noticed that the response in T3 had the appearance as seen in Figure 20. Approximately
1.7 – 2.1e\(^{-4}\) s after the response in T2 a response could be observed in T3. A much more significant response did tough appear 4.5 – 4.7e\(^{-4}\) after the first response. The two different behaviors was thought to be caused by the \(S_0\) and \(A_0\) mode, and since the difference in distance between T2 and T3 was roughly 46 cm, corresponded to an estimated wave propagation velocity of 978.7 – 1 022.2 m/s and 2 211.5 – 2 721.9 m/s.

Figure 20. Time difference between response in T2 and T3.

That it de facto is the \(S_0\) and the \(A_0\) modes, or at least one of the symmetric and asymmetric modes, could be strengthened by measuring with transducers T1 and T2, while using transducer T3 as the actuator. It could then be seen that the sensor between the laminate and the core did indeed, during the first time frame, pick up a mirrored signal compared to the one at the top of the laminate. The signal then became similar in the sensor at top of the laminate (Figure 21). Trying to estimate the propagation velocity from the time plot of the sent pulse did however not give a specific value since it was very difficult to distinguish the \(S_0\) mode form the \(A_0\) mode and their reflections and the overhearing if the sent pulse was to be measured as well. It could however be concluded that the velocities calculated from the impact were realistic since it could be seen that the \(S_0\) mode had a velocity of 2 500 – 3 500 m/s and the \(A_0\) had a velocity of 500 – 1 200 m/s depending on which frequency that was examined. It can also be seen in Figure 21 that the \(A_0\) mode seems to be dominant for in the plate.
After the hole had been enlarged from 6 mm to 8.7 mm the peak-to-peak and RMS values were compared again. For both the peak-to-peak and RMS value a decreased could be seen (Figure 22 and Figure 23).

Figure 21. Received pulse response in T1 and T2 with T3 used as the actuator.

Figure 22. Comparison of peak-to-peak value for the plate before, with the 6 mm, and with the 8.7 mm hole.
Figure 23. Comparison of RMS value for the plate before, with the 6 mm, and with the 8.7 mm hole.

When comparing the frequency content between the sent pulse, the undamaged plate, the 6 mm hole and the 8.7 mm hole, it could be seen that there was a clear difference depending on the excitation frequency, both in how good the repeatability would be for a given frequency, but also in how large of a difference the holes would entitle. Some observations that could be made were:

- For low excitation frequencies (1-3 kHz) a greater diversity between the different measurements were obtained. Despite that low frequencies entitles longer wavelength, this frequency range still appears to the interval where the most significant difference can be observed between the three different cases (undamaged, 6 mm and 8.7 mm hole).
- In the range (4-9 kHz) an increase in amplitude at 6 kHz for both cases with the hole compared to the undamaged plate. With these excitation frequencies a difference can be seen in the entire interval 5-9 kHz, even though it does not seem to be a consistency when comparing the change 6 mm and 8.7 mm.
- An interesting conclusion that could be drawn was that although the pulse was sent with frequency 10-12 kHz, the difference in the response content did nevertheless appear around 8 and 14 kHz. Thus are the changes occurring not primarily dependent on the excitation frequency but rather the properties of the plate and the damage.
- In the entire excitation range 11-18 kHz a significant dip can be observed at 14 kHz for the two cases with holes. This is a very interesting observation, mainly because it is consistent over such a broad frequency range, but also because the enlargement of the hole essentially only led to an increase of this phenomenon, also over the entire frequency range.
- For higher excitation frequencies some changes can be seen in the response around 19-21 kHz up to 24 kHz, this is however mainly with the larger hole. With a frequency of the pulse of 25-30 kHz there is basically no difference at all between the damaged plate and the undamaged plate.
It could also be seen that a delay indeed could be observed when comparing the time signal for damaged plates with the undamaged plates (Figure 24). How significant this effect was did however depend on the excitation frequency, and it seemed to be most notable in the range 6-14 kHz. For the highest frequencies this could not be seen at all. The larger hole seemed to entitle a larger effect for most of the frequencies, but this was not consistent.

![Received pulse, 7 kHz](image)

**Figure 24. Delay due to damage at 7 kHz.**

The attempts to create a black box model of the plate before and after the hole had been drilled did not lead to useful results. This was mainly due to a lack of knowledge of system identification in combination with a tight time plan. The same was true for the wavelet analyze that was attempted.

### 6.2 FOGV

When knocking on the FOGV it could be seen, as expected, that the location of the impact had an even greater influence than it had on the plate, due to the much more complex geometry. It could however also be seen that there was no obvious difference between the two sensors S1 and S2 (Figure 25 - Figure 27). When knocking close to sensor S1 that was the sensor which gave a slightly larger amplitude for the response, the same were true for S2, while knocking between the two sensors gave approximately the same amplitude. As mentioned, this was not true for the plate were sensor T2 always gave larger amplitude of the measured signal.
Figure 25. Comparison between sensor S1 and sensor S2 during impact close to sensor S1

Figure 26. Comparison between sensor S1 and sensor S2 during impact between S1 and S2.
As mentioned, sending pulses through the FOGV required a higher voltage due to the much stiffer structure. In spite of the increased amplitude of the output, the response was considerably smaller that for the plate, (Figure 28 and Figure 29). As can be seen there is a wave pulse almost simultaneously as the sent pulse which dominates the response in both S1 and S2. Since S1 is placed directly beside the actuator A1, the response in that sensor should be detected before the response of the sensor S2. This is however not the case and since the overhearing in the DAQ unit has been subtracted in the same way as was done for the plate, it is likely that this pulse exists due to overhearing between the cables (since they were not twisted) within the FOGV.

A very interesting finding was that for the FOGV the excitation frequency that gave the “best” response varied quite a lot depending on if sensor S1 or sensor S2 were considered. For lower frequencies, 7-15 kHz, the amplitude in S2 is greatest while for higher frequencies 22-30 kHz, a better response can be seen in S1, (Figure 28 and Figure 29).
Figure 28. Response in S1 and S2 at 12 kHz

Figure 29. Response in S1 and S2 at 26 kHz
7. Discussion

Although some adversities have been encountered, mainly with the hardware, many interesting things have been uncovered. There seems to be no doubt, neither in the results obtained nor in the literature reviewed, that Lamb waves has a great potential for damage detection. A clear decrease can be seen both in the RMS and the peak-to-peak value which is not a surprise. As suggested by (Mustapha, et al., 2011) there also seems to be a change in ToF when the pulse interacts with the damage. The results also shows that a larger damage causes a larger decrease for both RMS and peak-to-peak value, which seems like a reasonable result. The results also suggest that larger damage causes a bigger delay even though further research is needed. The hypothesis that the most significant change would occur at the frequency were the overall largest peak-to-peak value appeared seemed to be a rather good assumption, although it cannot be said with certainty that 7 kHz is the optimal frequency. An excitation frequency in the range 6.5-9 kHz does seem to be the optimal for detecting damages in the plate. A more precise examination with a finer interval would be needed to determine the best frequency. This is however something to consider for further research on the FOGV.

As concluded by (Raghavan & Cesnik, 2004) it was found that the smaller sensor was significantly more sensitive compared to the large ones regarding the ability to detecting signals. Some attempts were also made to use the transducer T4 as the actuator. Since the area of T4 is smaller less energy is requires to bend the actuator when sending a pulse. This could be worth considering if there are problems obtaining a good enough pulse in the FOGV’s. The length of the PWAS currently used is 5 cm, according to (Raghavan & Cesnik, 2004) this means that, if the propagation velocity is 600-800 m/s, the optimal frequency for sending pulses with this actuator should be 6-8 kHz, which agrees really well with the obtained results from the measurements on the plate. No attempts to detect reflections caused by the damages have been made. Because of the relatively low frequencies used, it is likely to assume that no reflections would be possible to observe since the wavelengths are too long and the distances too short. An excitation of 300 kHz is mentioned as a “sweet spot” for pulse-echo studies by (Giurgiutiu, et al., 2003). If a system with piezoelectric elements were to be implemented, it could very well be used to send both low and high frequencies. This, however, puts some demands on other hardware in the system, but a combination of different approaches is probably yet necessary to achieve a sufficient SHM system.

For the plate a large difference could be observed between the different sensors. It is difficult to tell which factor causes this difference, but most probably it is caused by the way in which the plate was manufactured where the PWAS and the core where attached with glued directly on to the carbon laminate. This most certainly entailed some difference between the two sensors and the ability for the wave to propagate through the plate. A less likely explanation is that there could be a difference in sensibility of the sensors. In the FOGV the PWAS are embedded before curing and attached during the RTM process. This method should ensure that there are no differences in the attachments of the sensors, and indeed it does not seem to be any differences in sensibility between the sensors in the FOGV.

Since there was only one plate, and this unfortunately had to be used even after the impact test had been carried out and two delamination damages had been caused, it is necessary to ponder how much of an influence these had. Another thing to consider is that the hole was drilled in the larger of these damages. This mean that in some way the comparison is made between a plate with a delamination caused by an impact and a plate with a hole instead of undamaged plate and a plate with a hole. In some way it would have made more sense to drill the hole in a third location even though this
probably would have caused even more complex wave propagation. To have access to more than one test plate had been incredibly useful. To be able to use more test objects had made it possible to verify that the results are transferable to another non-identical plate, but it had also made it possible to compare different types of damage.

The most interesting result were the very distinct change at 14 kHz when the comparing the frequency spectra between the undamaged plate, the plate with the 6 mm hole and with the 8.7 mm hole. The possibilities of substantially looking at and comparing the frequency content between a damaged and a undamaged structure does not seem to be a common approach. In the previous research it is mainly the time domain response and reflections that have been studied. What the frequency change at 14 kHz depends upon is hard to tell, but it is likely to believe that the wavelength at 14 kHz is closely linked with someone dimension of the plate or damage. Some possible dimensions could be, the width of the plate, the dimension of the hole, the plate width left next to the hole, the length or width of the actuator or the length or width of the sensor. It would have been very interesting to do further investigations, preferably on a larger plate without any edges close to the damage. To see how the type and location of the damage would affect the results. This would of course also require a number of identical undamaged test plates. If time had allowed it would also have be interesting to see if a similar phenomena could be observed for the FOGV’s.

As (Li, et al., 2015) concluded the time of flight is a good parameter to use for SHM since it is not influenced of external vibrations. Since the proposed component in this case is placed behind the fan in a turbofan engine there will without doubt be external vibrations. This could of course be a problem if the frequency content is supposed to be a determining factor or if the noise from the engine have dominant tones in a frequency range that complicates SHM. Given the sensitivity of the transducer and the small response a transmitted pulse caused in the FOGV it is hard to predict if it is even possible to implement a system operating while in flight. It could however very well be that noise from the engine is in a different frequency range and is simple to filter out.

Given the large effect the boundary conditions and the layup of the plate had on the measured signal one must consider how an SHM system like this would be affected if implemented in a running airplane engine. Very small changes of the load and the tension in the material would definitly have a huge influence on a pulse traveling though the material.

It is known that the laminate in the FOGV is slightly thicker than the one of the plate. As can be seen in equation (1) – (5) the material properties also have an influence of the propagation velocity and since the FOGV probably does not have the same density, fiber content etc is it expected that the propagation velocity increases. This will then entitle a longer wavelength and it is therefore reasonable that the optimal excitation frequency for the FOGV is higher. Due to the rectangular shape of the actuator and the placement of the sensor S2 (adjacent to the long side of A1) it seems very logical that the excitation frequency of the cross-direction of PWAS will be a lot higher. All of this agrees really well with what (Raghavan & Cesnik, 2004) have shown, equation (6). This is however a problem if the idea is to compare the response in S1 and S2. A better approach would be to place the sensor S1 in front of the short side of the actuator. Another solution could be using a circular piezoelectric element as the actuator. This would probably be the best solution since a circular actuator does not have the distinct frequency related characteristics that a rectangular actuator has.

Both the attempts of creating a black box model of the system and to conduct a wavelet analysis were unsuccessful. However, both of these methods are probably good approaches that could provide
further information about the system and can definitely be worth looking in to more deeply in future research.

Knocking on the structure and examine the frequency spectra does not seem to be a suited approach since the response varies a lot due to the location and the energy of the impact. The sensors, however, are sensitive to impacts and could probably easily be used to detect an impact in real time. If every FOGV were equipped with one PWAS that would be sufficient to determine that a FOGV has collided with something. It is also not that farfetched to assume that the energy of the impact could be accurately determined. Such a system could probably be implemented without too much difficulty, thereby give an indication when an FOGV have been hit and need to be inspected. Since the FOGV is a composite structure the wave propagation velocity can vary slightly in different directions, but if three or more PWAS were to be implemented in a FOGV it would be plausible to also determine the location of an impact. For larger structures this could be worth to consider, but for a small and easily replaceable structure like a FOGV it is most certainly more efficient to only detect if an impact have occurred.

It does not seem completely foreign to implement a system for detecting impact and to facilitate maintenance. However, going from there to a systems operating in real-time can be a very large step depending on factors such as disturbance from the engine and the changes of the boundary conditions while in flight. Things like temperature and humidity may also affect the material and its properties.

7.1 Future Work

There is still a long way to go before a functioning SHM system can be implemented for actual use. The next step in this process should be to damage one of the manufactured FOGVs to examine whether similar results as for the plate can be obtained. If this is the case, the next step should be to investigate how different types of damages affect the measured signals. There is also a lot of work to be done with using higher frequencies, both to detect reflections, but also to investigate how the sensitivity and resolution is affected by this aspect. It has been shown that damages as small as 25% of the wavelength has been detected (Díaz Valdés & Soutis, 2002). In these tests, the hole was 6 mm and the wavelength is estimated to be somewhere between 2 cm and 2 dm for the A₀ mode, depending on frequency. For future work it would be of interest to look at how small defects that can be detected and how this is related to excitation frequency. Close investigations to better understand why the frequency 14 kHz is canceled out are definitely needed. This can be accomplished either by enlarging the hole even more or by conducting the same measurements on a plate with a similar damage but with larger extension. That would ensure that the change occurs due to the damage, reduce the influence of edges and rule out that the change is caused by the dimension between the edges and the damage.

If new FOGVs are to be manufactured, it should be considered to use a circular actuator but it probably still is a good idea to reposition S1 so that it lines up with S2 if the idea is to compare these two. An buffer amplifier with amplification 1 to 1 should preferably be purchased and connected between the DAQ device and the amplifier connected to the PWAS to rule out the limitation in DAQs ability to deliver enough current.

For further research more focus is recommended to be laid upon the impact detection, which only has been of secondary concern during this work. It would also be interesting to see if a correlation between detected amplitude and impact energy can be found. The DAQ device can however only handle signal with amplitude ±10 V, and high energy impacts will cause the signal to become saturated. In case of further investigations, this problem has to be addressed.
8. Conclusion

The PWAS are very sensitive to impacts and to use a sensor to indicate that a FOGV has been hit by a foreign object is most certainly possible. The results also suggest that, if desirable, three or more PWAS could be implemented in a FOGV to get a location of the impact. It is also possible that a correlation can be determined that relates the measured amplitude to the impact energy. More research is however needed.

Lamb waves do indeed seem to have a great potential for detecting damages in thin plates and there is reason to believe that the system with piezoelectric elements similar to that implemented in the FOGVs developed at GKN could be used to detect cracks, delaminations, ply gaps, notches and porosity. This has been shown in previous studies, and the results obtained in this project support these conclusions. A decrease in both peak-to-peak and RMS values has been possible to identify in the damaged plate compared with the undamaged plate. A delay of the transmitted pulse seemed to occur when the pulse had to interact with a defect and the delay did also seem to be greater for a more notable damage. When a hole had been drilled in the plate, changes occurred in the frequency content of the received pulse. The changes did not seem to depend on frequency of the transmitted pulse, but rather because of the damage. An enlargement of the hole did entail different changes in some ranges of the frequency spectra, but increased the effects of the small hole in other parts of the spectra. More research is needed here as well to determine how various defects and different locations of the damage are affecting a wave pulse that interacts when sent through a damaged structure.

The greatest limitations encountered during the project have been problems with the hardware. The amplifiers both had their own problems which had to be addressed. The restrictions on the DAQ device, was yet an even larger limitation. Its ability to transmit sufficiently pulses of high frequency and amplitude, its ability to deliver enough current but also to achieve high enough sampling rate for the higher frequencies and the possibility of detecting signals with amplitudes of more than ±10 V are all factors that have to be considered for future work.

A circular actuator in the FOGV is likely not as dependent on excitation frequency and could therefore be preferred over a rectangular actuator. If a rectangular actuator is to be used the sensor S1 should be placed in front of short side of the actuator instead of the next to the longer side, which probably would provide far more useful information from sensor S1.
Bibliography


[Accessed 26 02 2016].


Appendices

Appendix A – Experimental Setup

The experimental setup is shown in Figure A1. The output signal from the DAQ device (seen to the right) was connected to the amplifier (seen to the left). The output was also directly looped back to one of the inputs on the DAQ. The output of the amplifier was connected to the transmitter T1 located between the laminate and the foam core and the sensor T4 was connected to the DAQ device. The DAQ device was then connected to a computer from which the LabVIEW programs were controlled. The picture shows the second of the two amplifiers used. The hardware was however connected in the same way with the first amplifier, with the only difference that an extra power supplier was needed to power the amplifier.

![Figure A1. Experimental setup, second amplifier.](image)

To detect impacts the transducers on top of the plate (which can be seen in the picture) were used. When these types of measurements were done, both T2 and T3 were connected directly to the input of the DAQ device.

**Hardware used**

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Manufacturer</th>
<th>Model</th>
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<tr>
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<td>NI USB – 6351</td>
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<tr>
<td>Amplifier 1</td>
<td>Physik Instrumente</td>
<td>E – 413. D2</td>
</tr>
<tr>
<td>Amplifier 2</td>
<td>Falco Systems</td>
<td>WMA - 300</td>
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<tr>
<td>Larg PWAS</td>
<td>Physik Instrumente</td>
<td>P-876.A11</td>
</tr>
<tr>
<td>Small PWAS</td>
<td>Physik Instrumente</td>
<td>P-876.SP1</td>
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</table>
Appendix B – LabVIEW Block Diagram, Pulse

The block diagrams shown below are those created in LabVIEW for transmitting and receiving pulses of different excitation frequencies and for saving data, Figure B1 and Figure B2. The idea is that in the command window (not shown below) the desired frequency can be chosen. The data blocks outside of the two loops then, when the program is started, creates a 1 second long signal of the form of the equation in the pink box. The signal created is multiplied with a rectangular function (equation (13) is used to calculate the number of samples in the window) to get only one wave pulse consisting of 5 wavelengths. By pressing the Boolean operator in the command window the Case loop is activated and the DAQ device starts to read and save data, a few microseconds later the block called DAQ Assistant2 transmits a pulse. The Case loop is placed in a While loop, so when the data acquisition is done, a new pulse can be sent by pressing the Boolean operator once again.

Constructing the program this way made it possible to change the excitation frequency without changing the sampling rate or the number of samples to read which facilitated the handling of the data, it was also a simple way of creating a small delay before the transmitted pulse, which was necessary due to disturbances that often occurred at the moment the DAQ started to read data.

![Figure B1. Block diagram for sending and receiving pulses in the plate.](image)

Sampling rate for data acquisition was: 500 kHz, the number of samples to read was 50 k and the input signal range was ±10. The input ports used were ai1 for the sensor and ai7 for the sent pulse.
The same principle was applied for the block diagram used for the FOGV but, as can be seen in Figure B2, a small modification had to be made. An extra output port had to be added and the signal created on the outside of the case loop was duplicated to get two identical pulses sent from different ports at the same time.

Sampling rate for data acquisition was: 333.333 kHz, the number of samples to read was 33,333 k and the input signal range was $\pm 10$. The input ports used were ai4 and ai5 for sensor S1 and S2 and ai7 for the sent pulse.
Appendix C – LabVIEW Block Diagram, Impact

The block diagram created for detection of impact is shown in Figure C1. When running the program the data acquisition starts immediately and since the entire program is placed in a While loop it continues until the Stop button is pressed in the command window. If a signal with greater or smaller amplitude then the threshold level is detected the trigger is activated and the condition “ ≠ 0 ” is fulfilled. This causes the Case loop to switch from true to false and the number of samples specified in the trigger block is stored.

For the plate the threshold level was 1 V and the number of samples stored was 500 before the detected signal and 4500 after. For the FOGV the threshold level was 0.2 V and the number of samples stored was 500 before the detected signal and 9500 after.

![Figure C1. Block diagram for detecting impacts in the plate and the FOGV.](image)

Sampling rate for data acquisition was: 100 kHz, the number of samples to read was 50 k and the input signal range was ±10. The input ports used ai1 and ai7 for the plate and ai4 and ai5 for the FOGV.
Appendix D – Pulse Response, 1-30 kHz

The figures D1-D6 shows the pulse response for different excitation frequencies. The label on the y-axis tells which excitation frequency was used. Note however that the amplitude of the signal is voltage, and the distance between two frequencies corresponds to 1V.

Figure D1.

Figure D2.
Figure D3

Figure D4.
Figure D5.

Sent and received pulse, 1-30 kHz

Figure D6.

Sent and received pulse, 1-30 kHz
Appendix E – Comparison PSD spectra, 1-30 kHz

Figure E1.

Figure E2.
Figure E3.

Figure E4.
Figure E5.

Figure E6.
Figure E7.

Figure E8.
Figure E9.

Figure E10.
Figure E11.

Figure E12.
Figure E13.

Figure E14.

XVII
Figure E15.

Figure E16.
Figure E17.

Figure E18.

XIX
Figure E19.

Figure E20.

XX
Figure E21.

Figure E22.
Figure E23.

Figure E24.
Figure E25.

PSD 25 kHz

Figure E26.

XXIII
Figure E27.

PSD 27 kHz

PSD 28 kHz

XXIV
Figure E29.

Figure E30.