TRANSPORTATION EXCELLENCE FOR
WIND TURBINE NACELLE

A Master Thesis Report by

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Abstract

With the growing demand of renewable wind energy, logistics and operations associated with a wind turbine makes for compelling study and analysis. The study entails understanding of transporting a wind turbine nacelle from Denmark till Australia. The methods of transporting the wind turbine nacelle and the modes of transportation that are currently in use have been studied. Factors that are detrimental to efficient shipping have been reviewed with existing literature and analysed for a wind turbine nacelle. The two key factors that influence transportation namely humidity and G-force have been identified. Simple and cost effective solutions such as use of insulation material, use of desiccants to overcome the effects of humidity, use of shock absorber pallets to reduce shock and vibration have been proposed. For the damages caused to a wind turbine nacelle due to random causes, some suggestions to prevent such damages have also been provided.

**Key words:** Wind turbine – nacelle – transportation – humidity – shock
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VCI – Vapour Phase Corrosion Inhibitors

G – G force which is measured in multiples of acceleration due to gravity 
\( (g = 9.81 \text{ m/s}^2) \)

mG – milli G force
CHAPTER 1

INTRODUCTION

This thesis work is a study of the issues involved in transporting heavy, bulk product like a wind turbine nacelle. This involves studying the existing literature and understanding the various factors that affect transportation of products over a long period of time and using different modes of transport. In the next step the current shipping methods of a wind turbine nacelle using the shipment data from Denmark till Australia have been studied. Finally some suggestions to overcome the effect of such factors that have an effect on the shipping of the nacelle have been proposed. One of the biggest cost components associated with transportation damage is warranty and replacement costs. Hence, the main aim of the thesis work is to find a trade-off between packaging costs and damage costs.

1.1 Background

It is a well known that the energy demand is growing exponentially around the world over each passing year. Alternatives, renewable sources of energy such as solar, hydro, wind, biomass and bio fuels have been going through continuous technological development to match the growing demands. Of these, use of wind to produce energy is one of the popular methods. Also, it has advantages of being clean and waste free in converting wind into electricity. To produce energy from wind, wind turbines are used. A wind turbine can be considered as the reverse process of a fan – wind produces electricity instead of electricity producing wind. A wind turbine essentially has six major parts: tower column, nacelle, hub and 3 rotor blades as shown in figure 1.1.

![Wind turbine components](image)

Fig 1.1 Wind turbine components (Courtesy DOE/NREL)
In a wind turbine, the nacelle houses the key components of the wind turbine. This includes the gearbox, generator, controller and the drive shafts as shown in figure 1.2.

Fig 1.2 Configuration of a wind turbine nacelle

A wind turbine nacelle can weigh anywhere between 60 to 80 tonnes depending on the configuration of the wind turbine. So, to ship such a heavy load product is a massive task.

A typical nacelle is assembled at the site of the manufacturer and after assembling, the nacelle is sent to the port in Denmark from where it is shipped to Australia. This is usually done by means of a special truck designed to carry nacelle. The transportation of nacelle is subcontracted to specialist transport companies. Once the nacelle arrives at the port, it is placed in the holding area. Since nacelle is a delicate product with lot of high precision electronic and mechanical components, a special shipping vessel is required to transport nacelles. These vessels are fitted with special decks called as tween decks. There are cranes on board that help in loading and unloading nacelles. These cranes are a standard feature of the tween decks. After the nacelle is loaded, they are bolted to specially designed transport frames made from steel beams and the frames are then welded to the deck. The time spent at sea can be as long as three months till the nacelle reaches Australia. Once the nacelle reaches the port at Australia, it is sent to the customer erection site on road. All steps and processes involved in the transportation of nacelle have been studied.
1.2 Problems associated with transportation

Packaging plays a very vital role in transportation. The product must be protected from the time it is manufactured till it becomes available for consumer use. Some of the hazards [1] that could be expected during the time a product is transported are

- Shock
- Vibration
- Compression (loads from top)
- Atmospheric changes in temperature and pressure
- Moisture and water
- Atmospheric pollution

Besides these there are biological hazards like decay, contamination due to microbes. But the main hazard in transportation is sudden impact for various reasons. The schematic diagram that explains the different categories of damage that can happen during transportation is shown in figure 1.3.

Fig 1.3 Categories of damage during transportation (Courtesy Export Packaging)
When a product is packed and transported, hazards vary based on the mode of transportation.

During rail shipment, snatching can occur due to the starting and stopping of loosely coupled cars [1]. Shunting railcars may cause impact on the goods present inside. Vibration can occur depending on the type of railcar, condition of the track and the speed. For mechanical products, this can mean loosening of screws and fastenings.

Transportation on roads might cause vibration based on the speed of travel, road conditions and the condition of suspension systems of trucks.

There is no major cause of concern while transporting by ship. But, containers still experience vibration, tipping, rolling and shock loads. Hence, proper stowing is necessary to prevent such hazards.

Air transportation can be critical for liquid products. Since pressure decreases at high altitudes, leakage might occur. Turbulent air conditions at high altitudes might also lead to varying pressures.

In this thesis work, road and ship transportation have been focused.

1.3 Thesis problem and Constraints

Since the thesis work is based on transportation of a wind turbine nacelle, the following research questions have been framed.

- What are the current practices, procedures and facilities available for measuring the factors that cause damage during transportation of heavy bulk products?

- What are the current solutions being used and could be proposed to reduce the effects of factors that cause damage to a wind turbine nacelle during transportation?

There were some limitations that were considered during the course of doing the thesis work.

- Most of the deviations and abnormalities observed in the measurement could not be attributed to the exact cause of the deviation. This is because of the limitations of the data logging system and the blindness associated with the experimentation.

- Solutions have been proposed that make implementation immediate and cost effective rather than developing and testing new solutions over a long period of time.
- Research characteristics of qualitative approach like personal experiences and interviews were not carried out.

1.4 Research Design

Research design outlines the plans and the procedures for research that span the decisions from broad assumptions to detailed methods of data collections and analysis [2]. In this section, the need for choosing a particular research design is explained.

A research design depends on philosophical worldviews, selected strategies of enquiry and research methods as shown in figure 1.4.

![Fig 1.4 Framework for research design](Image)

A research that serves to explain the situation of concern or one that describes the causal relationships of interest was adopted. Data, evidence and rational considerations shaped the knowledge associated with the research. The standard of validity and reliability played a crucial role in the research. Thus, it can be inferred that the research pointed towards adopting a post positivist worldview for the research.

In order to provide a specific direction for the procedures in a research design, a strategy of enquiry had to be chosen. An ethnographical strategy involving studying an intact system in a natural setting over a prolonged period of time was adopted. This involved mostly observational data and the research process was deemed flexible.
Since the research involved posing test or instrument based questions and was based on performance and observational data, research methods point to a more quantitative method of conducting research. In addition, analysis and interpretation were statistical. But since certain aspects involved text, image and pattern analysis, a part of the methodology was qualitative.

These factors were selected based on the problem posed by the research, personal experiences of the researchers and those of the observations of experienced and trained personnel, and also on the audiences interested in the research.

The research methodology adopted can be viewed as a quantitative approach as it involves a post positivist worldview, experimental strategy and analysis using statistical procedures. But certain aspects of the qualitative approach such as an ethnographic design were borrowed.
CHAPTER 2
LITERATURE REVIEW

A comprehensive study and review of articles, books related to transportation, periodicals and research papers was conducted to understand the various factors that have an impact during transportation of heavy bulk goods. In addition to this, process specifications of the manufacturer of the wind turbine nacelle were studied to understand the measures taken during transportation. Further studies of the shipping practices of various cargo handling firms were carried out.

In this chapter, various research findings related to transportation problems and the methods employed in measurement of such factors have been discussed. The patterns that could be observed on the influence of these factors on transportation are understood.

Rissi et al. (2008) quantified and analysed the vibration that occurs during truck transport in Brazil [3]. The study was done using two types of trucks: small local trucks for local metropolitan distribution areas and larger tractor-trailers for cross-country transportation. Ten metropolitan areas in different regions of Brazil were selected for 1-day trips representing normal delivery. These trips encountered varying road surfaces (asphalt, concrete, stone and dirt). The long distance trips were done on highways that were more than 1200 km long. The vertical vibration levels were higher than the lateral and longitudinal levels as expected. A composite power density spectrum of all trips was provided to simulate truck transport in Brazil using random vibration test methods.

In a study, Singh et al. (2007) measured the vibration levels in truck and rail shipments of freight to various major metropolitan cities in India [4]. The study also compared the vibration levels in trucks versus those in railcars and developed lab-simulated vibration test methods to simulate truck and rail shipments. The data recorders were mounted directly on to the vehicle (truck and rail) platform base. Two replicates were measured for all rail and truck shipments between certain distribution networks. The results of the study showed that the measured vertical vibration levels are more severe than levels used for existing test methods. The truck and rail vibration data shows excessive lateral and longitudinal movement. There was a difference between vibration levels in ‘truck’ versus ‘rail’ shipments and are at different frequencies than those observed in North America and Europe.

Chonhenchob et al. (2010) conducted a study to provide a comprehensive understanding of the vibration levels observed for truck and rail shipments for major transportation routes in Thailand [5], one of the leading economies in the
Southeast Asia region. Data recorders were used to collect the vibration data which were then analysed in terms of power spectral densities. Vibration levels observed from various segments of transportation are presented in the form of power density spectrums. Composite spectrums that can be used to simulate the measured vibration conditions in Thailand were presented.

In a research at Amgen Inc. Wallin (2007) described how to develop random vibration profiles to meet one’s qualification needs [6]. The presentation also outlined minimum requirements that should be met to develop a random vibration profile. Data collection efforts were focused on collecting data from trucks and airplanes. Data from the truck were gathered by attaching four vibration data loggers to two trucks just behind the rear axle. The preferred approach to collect airplane data was to attach vibration data loggers directly to an airplane to gather the best possible vibration data. A high 20% and low 80% profile was created. Using the data gathered from this study, Amgen compared their data to ISTA’s data for an air ride truck in test procedure 3H. Based on this comparison of the data Amgen determined it has a high level of confidence in ISTA’s profiles. The data was averaged and smoothed following the same approach used for the truck profiles to create the Amgen Low Intensity Airplane Random Vibration Profile.

In a paper, Leinberger (2006) summarized the results from a twenty-month study of ocean container temperature and humidity conditions for shipments between Asia, Europe and North America [7]. While this study focused on ocean containers, the recorded conditions include sea, truck and rail transportation as well as periods of storage that might occur during a normal container shipment. A distribution of all data along with a detailed look at the extreme conditions was provided. Effects of container position on the ship and recorder position within the container were presented. The effect of the container contents was also discussed.

The research done by Peleg (1984) describes a specially developed transportation damage simulation test jig [8]. He developed an experimental evaluation of restoring and dissipative parameters, as used in a non-linear mathematical unit load model. He exemplified how these parameters might be evaluated by impact (shock) or vibration testing of corrugated produce shipping containers. The initial spring rate was found to be approximately equal in impact and vibration loading. The parameter expressing the non-linearity was significantly larger in vibration loading than in impact loading. On the other hand, both Viscous and Coulomb damping are significantly greater in impact loading than in vibration loading. The same modus operandi maybe used for determination of dynamic restoring and dissipative parameters of other products, such as cushioning foams and elastomer.
In the report provided by Forest Products Laboratory Forest Service (1979), an assessment of available data and information describing the common carrier shipping environment was conducted. The assessment included the major shipping hazards of shock, vibration, impact, temperature, and humidity associated with the handling, transportation, and warehousing operations of typical distribution cycles. Previous environmental studies and current data were reviewed and assessed for applicability to general type cargo design and/or evaluation. The data for each hazard were summarized in a format considered most useful to packaging engineers when such data are available. Hazards requiring further information and description were identified and discussed.

Ted Ling (2002) conducted an experiment to find out the impact of humidity inside a shipping container [10] used to store records of repositories. The container was placed in a location which had varying levels of humidity during dry and wet seasons. With the help of data loggers installed inside the container and inside the boxes which store records, it was found that the humidity inside the boxes was lower when compared with the humidity in the container. The results showed that when relative humidity levels exceeded more than 60%, the possibility of spores being developed and records getting damaged was very high.

In a research done by Saunders (2008), the effects of shock and vibration on transporting paintings [11] from one place to another have been discussed. With the help of data loggers, the levels of shock and vibration were monitored when a painting is transported or moved from one venue to another. Different modes of transportation, handling of paintings during such transportation have been discussed. Critical handling, loading and unloading points during transportation which lead to high levels of shock and vibration were also discussed. It was observed that the land and sea transportation resulted in a longer period of 'background' vibration in the range 0.5–1.0g, while the land and air shipment will be on the road for less time but will probably be exposed to shocks of 3–8g in the cargo areas at airports.

Hence, after reading the articles, it is understood that there are certain factors which have a direct effect in causing damage to the products during transportation. During intermodal transportation which involves transportation by truck and sea or truck and air, these factors must be considered and methods to measure such factors need to be implemented. Also techniques that could be employed to prevent damage must be put in place.

It is clear from the above literature review that vibration, humidity and shock are the major factors during transportation. With vibration, power density spectrums give information of typical vibration patterns during rail and sea
transportation. Data logger systems used during transportation can help in measurement of the factors that affect the product being transported. Based on information from data logger systems, the acceptable limits of vibration, humidity and shock can be derived.

Since humidity, G – force and shock are the major factors associated with transportation damage to a wind turbine nacelle, these factors are elaborately discussed in the following chapters.
CHAPTER 3
HUMIDITY DURING TRANSPORTATION

This chapter deals with one of the major factors contributing to damage while transporting a wind turbine nacelle. The significance of controlling humidity during transportation, current methods for measuring humidity and suggestions for effective humidity control has been discussed.

Humidity as a general term represents the amount of water vapour in air. Any material or product inside a container during transportation is subject to various difficulties. One such difficulty is the influence of moisture present inside the container and its impact on the cargo. The increase in temperature can cause air to get warmer making it hold more moisture. Once the temperature drops, the moisture gets condensed. The repeated fluctuation in temperature causes considerable damage to the critical components of the product inside the container.

Humidity occurs in two forms during sea transportation. They are container sweat and cargo sweat.

**Container Sweat**

It occurs when the skin of the container is cooled to a temperature below that of the dew point of the air enclosed within the container. This results in water droplets forming on the interior roof and side panels and dripping down on the cargo causing mould and water damage. Cargoes that spontaneously heat from within can increase the problem. For example, a cargo loaded in the tropical belt in warm conditions with high relative humidity transported to cold winter conditions in Europe is bound to have container sweat. This happens since the temperature inside the container is below the dew point of the air inside the container which causes condensation. By ventilating the container, the effect of container sweat can be reduced.

**Cargo Sweat**

It occurs when the surface of the cargo is cooler than the dew point of the air enclosed within the container. Droplets of water then form on the surface of the cargo. In this case, a cargo loaded in cold European conditions and transported to the tropics will gradually heat up during transit to the warm moist climate. With cargo sweat, ventilation must be avoided to maintain the equilibrium between the cargo temperature and the outside air.
3.1 Terminologies associated with humidity

To get a clear understanding of container sweat and cargo sweat, certain terminologies associated with humidity [12] are described below:

**Saturated Air**

For a given atmospheric pressure, air holds more water vapour at higher than lower temperatures. The maximum amount of water vapour contained in a cubic metre of saturated air decreases with a decrease in temperature.

**Dew Point**

It refers to the temperature at which a sample of saturated air will condense. Warm air has more capacity to support water vapour within it than cold air.

**Condensation**

It occurs when moisture laden air releases its water vapour on to the surrounding surfaces in the form of water droplets. For condensation to occur the following conditions need to be present:

- Temperature gradient (Between inside and outside the container)
- A source of water vapour (moisture)

3.2 Humidity in shipping wind turbine nacelle

A wind turbine nacelle can weigh as high as 70 tons. A nacelle has various critical components and influence of moisture and humidity on such critical components during shipping directly relates to reliable and efficient functioning of nacelle after the wind turbine is installed.

When a nacelle is loaded onto a specially made transport frame at the port terminal in Denmark, it becomes a closed system and has its own weather system inside. As soon as it is stowed, air gets trapped inside it. The amount of air that gets trapped is dependent on the temperature and humidity at the location of loading the nacelle. This means that there is bound to be moisture inside the nacelle. Any container cannot be fully airtight. So moisture levels inside the nacelle will be varying.
3.3 Measuring humidity

When a nacelle is being shipped from Denmark, a humidity sensor is fitted inside the drive train which helps in measuring humidity levels at frequent intervals of time. Additionally, there are two humidity sensors similar to the one shown in figure 3.1 are placed in the nacelle.

![Humidity Sensor](image1)

**Fig 3.1 Humidity Sensor**

The sensors are connected to an external power outlet and also feed into a data logger system. The humidity sensor is placed inside the drive train of a wind turbine nacelle as shown in figure 3.2.

![Humidity sensor placed inside the drive train](image2)

**Fig 3.2 Humidity sensor placed inside the drive train**
3.4 Humidity measurements on shipped nacelles

The data logger system which is fitted along with the sensors on the nacelle measures humidity at constant time intervals for the entire journey at sea. One drawback of the data logger system is its inability to access online data during shipping at sea. After the nacelle has reached Australia, the data logger system is then sent back to Denmark where data stored in it is studied and analysed. So far, a set of eight nacelles that have been shipped to Australia with data logger systems installed on each nacelle were studied. The humidity measurements from the data logger systems of a few nacelles are shown below.

In one of the nacelle that was shipped with a transportation time of three months, the relative humidity level as shown in figure 3.3 is above the set requirement of 65%. The maximum relative humidity observed inside the drive train is 68%.

![Humidity inside gear box above standard limit – Box 8](image)

In one of the other nacelle that was shipped with a transportation time of two months, the relative humidity level observed inside the drive train is 46%. This means the humidity level is within the set requirement of 65% as shown in figure 3.4.
Hence, for the nacelles that has been shipped from Denmark to Australia along the same sea route show different levels of humidity inside the gear box and inside the nacelle as a whole. Since humidity levels exceed the standard set limits, it requires attention to find possible solutions to reduce the variation in humidity levels during shipping.

### 3.5 Humidity control during handling

According to Leinberger (2006) any cargo goes through three stages of shipping. The first stage is the road transportation and brief periods of storage during which the cargo undergoes daily cycles of temperature and humidity. The next stage involves the time at sea which maybe the longest stage. Daily variation in temperature and humidity is usually very minor. Any variation takes much longer time compared to the first stage. The final stage is the freight unloading process onto trucks or trains during which temperature and humidity cycles are extreme [13].

Figure 3.5 describes a typical study conducted (by Leinberger) for a shipment from Japan to Portland (USA). It can be seen that fluctuations in temperature and humidity levels are maximum during handling [13]. It is imperative to control the excess variation observed during handling, loading and unloading of the cargo.
Fig 3.5 Typical shipment stages and corresponding humidity levels (Leinberger 2006)

3.6 Solutions for reducing humidity levels

The humidity level inside the nacelle and inside the gearbox of the nacelle must be controlled right from the time the nacelle is assembled completely till it is shipped to the destination. This also includes the handling of the nacelle at the assembly plant and when it is at the port terminal. Hence, solutions to control humidity have been proposed below during the shipping of a nacelle.

3.6.1 Warehouse protection

When a nacelle is assembled at the plant, it is stored in an open space environment till the time it is shipped as shown in figure 3.6.

Fig 3.6 Storage of assembled nacelle
When an assembled nacelle is stored in such an open environment, it is susceptible to high levels of variation in temperature and humidity. It is exposed to extreme weather conditions like sunlight and rain. The nacelle will be stored in such open environment for as long as a week before it is shipped.

To prevent the nacelle from being exposed to such extreme weather conditions, one simple solution could be the installation of a protective ceiling or roof at the warehouse where the nacelle is being stored. This will be a onetime investment which involves minimum costs.

### 3.6.2 Insulation

In his study, Leinberger (2006) describes the effect of container contents and its effect on variation in humidity levels [13]. According to the study, when a container filled with plastic boxes and another container filled with fibreboard boxes are exposed to same levels of humidity for the same amount of time under ocean shipping conditions, fibreboard boxes had much less humidity variation than plastic boxes as shown in figure 3.7. This gives a direct relationship between the contents in the container and its effect on relative humidity inside the container.

![Graph showing temperature and humidity variations](image)

**Fig 3.7 Container contents and its effect on humidity level**

In the case of a wind turbine nacelle it is shipped from the assembly plant to the port terminal. At the port terminal, the nacelle is bolted onto the transport frame. As mentioned earlier, the nacelles that have been shipped from Denmark to Australia have shown huge variations in humidity level. So, another solution
that is proposed to reduce the variation in humidity is to use a fibreboard insulation cover to protect the nacelle.

Fibreboard boxes have the advantages of being light weight, efficient, cost effective. One main factor to select fibreboard boxes is its resistance to moisture absorption. Fibreboard boxes come in different grades based on moisture resistance and strength capabilities. Medium density fibreboard box is more suitable for the application of enclosing a wind nacelle since it can be used in situations of prolonged exposure to high levels of humidity [14].

**3.6.3 Positioning in ship**

Once the wind turbine nacelle arrives at the port terminal, it is loaded into the ship. Since the nacelle is on voyage for a period of about three months in sea, positioning it in a particular location of the ship will significantly impact the humidity levels that vary inside the nacelle. Taking this into consideration, it is always favourable to stow the nacelle below deck and avoid on deck stowage. The reason is to shield the container from exposure to sunlight during daytime. Exposure to sunlight has a direct effect on the variation in container temperature. This was found out by (Leinberger 2006) comparing containers stowed on deck and below deck and studying their temperature variations inside [13]. Containers stowed below deck showed much less temperature variation than those stowed on deck.

**3.6.4 Desiccants and alternative methods**

The desiccant is a substance that helps in absorbing or adsorbing water. In a way, it helps to reduce the moisture present inside a closed container. The process of using desiccants to reduce moisture is called as desiccation. It is used to remove humidity and prevent degradation of products inside the container. Some of the most commonly used desiccants include silica gel, calcium sulphate, etc. With the help of desiccants, it is possible to reduce the moisture present in the air.

When a wind turbine nacelle is being shipped, it is placed in a holding area at the port terminal. This means that there is the probability of moisture being present in the air inside the nacelle. Since the nacelle travels on a long journey at sea, presence of moisture can cause considerable damage to its components. Hence as a measure to prevent condensation, silica gel can be used as a desiccant. However, using silica gel poses a problem. Silica gel is effective when used in completely airtight spaces like cardboard cartons [15]. For a wind turbine nacelle which is huge and heavy, it is ineffective to use silica gel as a desiccant because the nacelle has lot of empty spaces inside it.
In the current shipping scenario of the wind turbine nacelle, a dehumidifier is being used during transport by vessel. The dehumidifier works till the vessel reaches Australia where there is availability of power supply. From the time after it reaches the port at Australia till it reaches the erection site, there is no power supply. So dehumidifier becomes idle in the absence of power supply.

Thus, there are other alternative methods for reducing moisture and preventing corrosion during shipping. A few of them are listed in table 3.1.

### Table 3.1 Alternative Methods of Moisture Removal and Corrosion Inhibition

<table>
<thead>
<tr>
<th>Type</th>
<th>Properties</th>
<th>Examples</th>
</tr>
</thead>
</table>
| Vapour Phase Corrosion Inhibitors (VCI) | Continuously releases vapour with powerful anti corrosion properties protecting steel and other metallic surfaces. | • VCI powders  
• VCI oils  
• Polymer films  
• Tablets  
• Water soluble VCI products  |
| Desiccator plugs              | Indicates and removes moisture but does not control corrosion. Plugs are sealed to walls of containers and easy to visually inspect. | Aluminium or zinc based refillable plugs and tubes containing desiccants  |
| Barrier Packaging             | Consists of an aluminium layer which has a low moisture transmission rate sandwiched between a polyester layer which gives strength and polythene layer which provides sealing [16]. | Box liners, covers with sealed bottoms, covers with and without bottom, etc.  |

One other solution that is suggested to reduce the effect of moisture inside the container is to reduce the amount of empty spaces. In his study, Leinberger has discussed that temperatures of empty spaces in the container are less moderate than the temperature surrounded by the packaged products [13]. So, empty spaces can be avoided by using dry bags. Dry bags are made up of roasted moler clay mixed with calcium chloride.
This chapter deals with another major factor that contributes to damage during transportation. The effect of G – force and shock on a particular product during transportation has been discussed. The current method of measurement and possible solutions to reduce the effect of G – force and shock during transportation has also been discussed.

Any object or product is subjected to shock or G - forces when it is handled or transported from one place to another. These forces can be caused due to many reasons – road condition, improper packaging, absence of shock absorption materials, etc. Products that are sensitive to impact must be handled very carefully since it has greater effect on the efficiency and reliability of the product. Steps must be taken to ensure that the effect of shock and G – force is very minimal on the product that is being shipped.

Mechanical shocks arise due to the following factors:

- Accidental and deliberate drops during manual handling
- Falling over from pallets
- Sudden stops
- Vehicles hitting potholes, curbs
- Packages rolled or tipped over

Damage to the cargo arises due to containers dropped flat as opposed to drops on corners or edges transmit very little shock to the cargo [17].

4.1 G - force and shock determination

In the shipping of a wind turbine nacelle from Denmark till Australia, sensors help in measuring the G – forces that act on the gearbox. A typical sensor used to measure G – forces is shown in figure 4.1.
This G – force sensor is placed on the outside of the gearbox as shown in figure 4.2. It is in turn connected with the data logger system which records the values of G – forces acting on the gearbox at regular intervals.

In addition to G – force sensors, Drop 'N' Tell® damage indicators are also used to identify instances of heavy impact being experienced during its shipping. These Drop 'N' Tell® indicators are placed on the outside of the gearbox as shown in figure 4.3.
Drop 'N' Tell® damage indicators of 5G, 10G and 15G configurations are used while shipping the nacelle. The Drop 'N' Tell® impact indicator is aligned with the arrow pointing to the direction of shock to be monitored. From the above figure, it is clear that the Drop 'N' Tell® impact indicators are placed in three directions to give the three dimensional readout.

If there is an instance of heavy impact or shock during shipping, the indicator is tripped and this gives an understanding of the magnitude of the impact. For example, if the 5G Drop 'N' Tell® impact indicator gets tripped and the 10G Drop 'N' Tell® does not get tripped, this means there has been a shock impact of more than 5G but less than 10G.

4.2 Allowable acceleration levels

When transporting a wind turbine nacelle by truck or train or ship and if it experiences a heavy shock, it bears a direct influence on the mechanical components present in the nacelle. Keeping this in mind, standards for allowable limits of G – forces have been devised. The graph in figure 4.4 shows the permissible acceleration levels that must be maintained throughout the shipping time of the nacelle as prescribed by the manufacturer.
It is evident from the graph that the maximum allowed acceleration level during transportation of nacelle is 0.4 G. During the initial period of transportation, G – forces as high as 10G are allowed. This is because of the handling of the nacelle in its initial hours of transportation.

Here, a turner gear is used by the manufacturer during shipping to avoid potential damage that could be caused to the gearbox and generator bearings when the wind turbine nacelle is being transported overseas or by rail.

If the observed acceleration values during shipping stays below the green curve, then there is no real necessity to use a turner gear to rotate the gearbox. In case the values of G – forces measured during transportation lie between the green and red curve, then it is mandatory to use a turner gear to rotate the gearbox intermittently during transport. Rotation of the gearbox is done once every 12 hours. If the values of measured G – forces are above the red curve, further transportation of the nacelle is not advisable.

But the limitation with using a turner gear is that it requires constant power supply. Also, use of turner gear is very expensive and labour intensive. Hence, with the control of G – forces within the allowable limits, use of turner gear can be avoided and hence savings in cost and time. The image of turner gear coupled with the gear box of the nacelle is shown in figure 4.5.
4.3 G – force measurement on shipped nacelles

For the set of nacelles that have been shipped from Denmark till Australia, data obtained from the data logger systems on G – forces have been studied. It has been observed that there have been no major disturbances from G – forces or shock during transportation. On a couple of occasions, G – forces have exceeded permissible levels during the handling of the nacelle.

In one instance, the G – force on the nacelle (Box 7) has been observed to peak at 1.480 G.

The graph in figure 4.6 shows the fluctuations in G – force recorded on one particular day during transportation.
In the second instance, the peak value of G – force on the nacelle (Box 4) was at -0.950 G. The negative sign indicates acceleration in the negative direction. The graph in figure 4.7 shows the variation of G – force on one particular day during transportation.

![Graph of G-force variation](image)

**Fig 4.7 Box 4 Peak value of G – force**

After studying the graphs, it has been understood that the maximum values of the G – force is not more than 2 G (or 2000 mG). This means that the Drop 'N' Tell® damage indicator has not been tripped during the entire period of transportation. Hence, this indicates that there has been no major shock or impact with the set of nacelles that has been shipped.

### 4.4 Suggestions to reduce effect of G – force and shock

From the data that has been studied on the shipped nacelles, it is evident that there is no major impact or G – force during shipping at sea. However, while the nacelle is being handled at the port terminal high values of G – forces are observed. Hence, to counter such problems, few solutions have been proposed.

#### 4.4.1 Shock absorbing pallets

When the wind turbine nacelle is being handled at the port terminal, use of shock absorbing pallets can help in reducing G – forces to a considerable extent. Just after the nacelle is completely assembled and is ready for shipping, it could be placed on the top of a shock absorbing pallet. With the nacelle resting on the shock absorbing pallet, it could be loaded onto the truck from where it is shipped to the port.
As seen in figure 4.8 the nacelle rests directly on the truck. This makes it prone to high levels of G – force during transport by truck. Some of the reasons could be the condition of roads, driving at turns and roundabouts, etc. By placing a shock absorbing pallet, it helps in reducing G – force during transportation by truck.

Highly vibration sensitive materials like glass products, precision equipments are transported using different modes of transportation with the help of such shock absorbing pallets as shown in figure 4.9 [18].

Since a wind turbine nacelle could be weighing as high as 70 tons and its dimensions being huge, customized designing of a pallet for a nacelle becomes a priority. The main factor to be considered is the load bearing capacity of the pallet. Such shock absorbing pallets could be designed either as a single big sized pallet or be designed modularly as multiple small sized pallets integrated into one single piece.

These shock absorbing pallets come in different forms and there are different materials used for shock absorption. Some of the shock absorbing materials that could be used are discussed below.
4.4.2 Shock Isolators

One form of shock absorption is by using shock isolators. The shock isolators are used as part of the shock absorbing pallets. These isolators can be made from different varieties of resilient media and each isolator has individual characteristics and properties. Based on the application use and load bearing capacity, isolators are chosen. A few of the varieties of shock isolators are described.

Elastomeric Isolators

Elastomeric isolators form one of the types of shock isolators. It has the advantage of storing high energy and also could be moulded into any required shape [19]. There are various synthetic elastomers each of which has different characteristics in addition to natural rubber. Some of the synthetic elastomers [20] are Neoprene, SPE\textsuperscript{®} I, BTR\textsuperscript{®}, BTR II\textsuperscript{®}, BTR VI, MEE, MEA, MEM, etc.

Of these, SPE\textsuperscript{®} I has applications in shipping containers as vibration and shock mounts. Also, natural rubber has high load carrying capabilities and hence could act as a good elastomer for reducing vibration. Apart from these, MEE and MEA have properties of vibration control [20].

These elastomers are sensitive to strain, vibration, frequency and temperature levels to which they are exposed.

Also, the elastomers have different mounting configurations that could be applied based on the severity of the application and the level of protection required for the product or equipment.

The different types of mounting [20] include

- Fully bonded
- Holder type
- Centre bonded
- Unbonded
Different mounting configurations are shown in figure 4.10. Fully bonded has far more performance characteristics when compared with centre bonded or unbonded configurations.

**Polyurethane foam**

One other material that could be coupled with the shock absorbing pallets is polyurethane foam or viscoelastic foam. Some of the major characteristics of polyurethane foam are shock absorption and damping of vibration. Also, it has the ability to recover very slowly back to its original shape after compression [21]. It has many applications in hospitals and medical industries. It can also be used for shock protection in packaging electronic equipments.

On the contrary, it also has very high sensitivity to humidity and temperature. Hence, it might not be able to withstand changes in temperature and humidity when the wind turbine nacelle is shipped at sea. Typical shapes of using polyurethane foam are shown in figure 4.11.

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**Fig 4.10 Mounting configurations of Elastomers (Courtesy RPM Mechanical Inc.)**

![Diagram showing different mounting configurations](image)

**Fig 4.11 Foam bumpers (Courtesy Pleiger Plastics Company, Washington)**
CHAPTER 5
OTHER TRANSPORTATION DAMAGES TO NACELLE

In the transportation process of a wind turbine nacelle, there are some major factors which have a direct effect every time a nacelle is being transported by ship. It is necessary to take proactive measures to prevent any damage to the nacelle from those major factors. Such factors have already been discussed in the previous chapters by analysing the data for the shipped nacelles.

In addition to the major factors, there can also be many other ways by which damage can occur to the nacelle. These damages are predominantly one time occurrences which cannot be predicted. Most of these damages occur either during transport or handling at the sea port. Often, such damages lead to additional costs, delay in delivery of nacelle to customer and ultimately reduced customer satisfaction.

Data on damages to nacelles that occurred for the year 2011 are studied and analysed. By ranking some of the damages that have occurred most often and are common, suggestions to prevent such damages are provided. Most of the damages that have occurred are found only after the nacelle has reached the erection site. This means that the damages have to be corrected and rectified before it is erected.

Studying the damages that have occurred with the nacelles during the year 2011, it has been observed that damages that occur due to transport form about 3% of the cases. This comes to about complaints received for 67 nacelles during the year 2011 which is quite a sizeable number.

The pie chart shown in figure 5.1 explains the different types of damages that have occurred with nacelles during the year 2011.
Fig 5.1 Nacelle damages for the year 2011
5.1 Nacelle damage due to transportation

Going further, the damages that have been caused to nacelle due to transportation have been studied specifically. The various causes for damages to the 67 nacelles due to transportation are represented in figure 5.2.

![Transportation Damages during 2011](image)

**Fig 5.2 Nacelle damage due to transportation in 2011**

Damages that have occurred to the nacelle during transportation are shown in the pictures below.

![Loosening of components](image)

**Fig 5.3 Loosening of components**

The damage of loosening of components to a wind turbine nacelle is shown in figure 5.3.
In figure 5.4 a visible damage of dent can be seen.

![Fig 5.4 Visible damage – dents](image)

Damage caused due to fire burn marks is shown in figure 5.5.

![Fig 5.5 Damage caused due to fire](image)

It is necessary to cut open the transport frame that holds the wind turbine nacelle at the port terminal at the destination site. This is done usually by gas welding. Damage occurs in the form of smoke dust settling down on electrical components as shown in figure 5.6.
Similarly, smoke dust settles down on transformer present inside the nacelle as shown in figure 5.7.

Discussion of the various factors attributing to nacelle damages caused due to transport, some examples and possible solutions to avoid such damages in future are mentioned in table 5.1.

Table 5.1 Factors, causes, effects and suggestions of nacelle damage due to transport

<table>
<thead>
<tr>
<th>Factor causing damage</th>
<th>Causes and effects of damages</th>
<th>Suggestions to avoid damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Third party transportation damage</td>
<td>• Manhandling by truck driver</td>
<td>• Efficient training to truck drivers</td>
</tr>
<tr>
<td><strong>Damages due to handling</strong></td>
<td><strong>Delay in sharing information of damage</strong>&lt;br&gt;<strong>Repair works done at port – delay in shipping and delivery</strong></td>
<td><strong>Better relations and communication with third parties</strong>&lt;br&gt;<strong>Employing strict quality assurance tools and methods</strong></td>
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<tr>
<td>---------------------------</td>
<td>-------------------------------------------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Hot works damage</strong></td>
<td><strong>Mishandling during loading, unloading, lifting and moving</strong>&lt;br&gt;<strong>Replacement of parts – cost addition and delay in time</strong></td>
<td><strong>Pre shipment testing such as tilt test, drop test, etc. to determine the effects of handling [17]and foresee issues that might arise during handling</strong>&lt;br&gt;<strong>Cushioning, insulation of internal components</strong></td>
</tr>
<tr>
<td><strong>Damages due to unknown reasons</strong></td>
<td><strong>Welding, grinding or cutting open frames from the ship deck</strong>&lt;br&gt;<strong>Burn marks, dust, smoke and rust causing additional repair and cleaning jobs of nacelle</strong></td>
<td><strong>Covering nacelles with steel bulkheads or woven polyester straps [22]</strong>&lt;br&gt;<strong>Use of fire blankets while cutting the transport frame from the ship deck and having them ready in case of a fire</strong>&lt;br&gt;<strong>Observing proper hot work procedures</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Loosening of components</strong>&lt;br&gt;<strong>Visible external damages like scratches, dents, etc.</strong></td>
<td><strong>Using better data gathering systems to find out causes, time scale and extent of damage online</strong></td>
</tr>
</tbody>
</table>
CHAPTER 6
CONCLUSION AND FUTURE RESEARCH AREAS

Studying the transportation procedure of the wind turbine nacelle and analysing data from the data logger system has helped in understanding that humidity and shock are the two major factors that are prone to cause damage to the components inside the nacelle. Controlling humidity must be of high priority since fluctuation in humidity levels can lead to damage of electrical and mechanical components. Humidity could be controlled by warehouse protection, insulation of the nacelle, appropriate positioning the nacelle in the ship and by the use of desiccants and other alternatives. Also, handling of the wind turbine nacelle to reduce shock and G - forces is important. This could be done by use of shock absorbing pallets, shock isolators and polyurethane foam. Also other ways by which damage could occur to a wind turbine nacelle has been discussed and suggestions for occurrence of such damages have been proposed.

Warranty costs and damage costs contribute to a big part of the cost of poor quality for a wind turbine nacelle. Hence, an optimum packaging solution has been proposed which is a trade-off between packaging costs and cost of poor quality as shown in figure 6.1.

![Fig 6.1 Packaging (vs) Damage costs](image)

Key learning points from working on the thesis include shipping techniques for bulk components, factors influencing transportation damage and methods that could be employed to reduce transportation damage. The research questions that were identified in the beginning have been answered to the maximum possible extent.
6.1 Future research areas

As mentioned earlier, there were constraints to be taken into consideration during the course of doing the thesis work. This provides the scope for many opportunities to do further research in the topic of transportation of wind turbine nacelles and other wind turbine parts. Since a wind turbine is one huge giant automated machine, challenges in transporting the various wind turbine parts are enormous. With the wind energy sector growing at a rapid pace, ensuring efficient and high quality transportation of wind turbines will make a huge difference in attracting more customers and increasing customer satisfaction. Also, it helps in reducing operation costs for the manufacturer of wind turbines.

- Transportation of wind turbine nacelles to offshore wind farms. Offshore wind farms are located in the sea and transporting a nacelle to an offshore wind farm and erecting it has further challenges.

- The handling of a wind turbine nacelle at the port terminal can be studied and analysed in detail. Precise understanding of the handling process and studying the effect of vibration will help in improved handling and shipping of the wind turbine nacelle.

- Improving or making changes in design to the nacelle that will directly aid and help in better transportation. Doing further research in design will lead to more light and compact nacelles which are convenient for shipping.

- Studying and analysing the transportation of nacelles when it is shipped using alternate modes of transportation. One area of future work that could be carried out includes transportation by rail network. Transporting wind turbine nacelles over long distances on land makes rail transportation more efficient and cost effective.
Literature References


