MAINTENANCE OF ELECTRICAL MACHINES:
INSTANTANEOUS ANGULAR SPEED ANALYSIS

Settore scientifico-disciplinare: ING-IND/13

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The North Face
Contents

Preface V

1. Introduction 1
   1.1. Maintenance of Electrical Machines ........................................... 1
   1.1.1. Projecting maintenance ......................................................... 2
   1.1.2. Monitoring settings .............................................................. 3
   1.1.3. Considerations ................................................................. 6
   1.2. Electromagnetic Excitations in Induction Machines ....................... 7
   1.2.1. Introduction ................................................................. 7
   1.2.2. Electrical parameters ....................................................... 9
   1.2.3. Theory of the development of flux in the air gap ....................... 9
   1.2.4. Radial force waves of electromagnetic origin ......................... 11
   1.2.5. Electromagnetic torque components ..................................... 14
   1.3. Faults in Electrical Motors .................................................. 15
   1.3.1. Fault diagnosis techniques ............................................... 15
   1.3.2. Monitoring a machine ....................................................... 17
   1.4. Characteristic Fault Frequencies in Induction Machines ............... 19
   1.4.1. Electrical faults ............................................................ 19
   1.4.2. Mechanical faults ........................................................... 20

2. Instantaneous Angular Speed 23
   2.1. Introduction ........................................................................ 23
   2.1.1. Counter based methods .................................................... 26
   2.1.2. Analog to digital methods ............................................... 28
   2.1.3. Incremental encoder ......................................................... 29
   2.1.4. Encoder measurement ...................................................... 31
   2.2. IAS Processing .................................................................. 36
   2.2.1. FFT processing ............................................................... 37
   2.2.2. Spectral aliasing ............................................................. 46
   2.2.3. Angular synchronous averaging ....................................... 48
   2.2.4. Encoder correction .......................................................... 48
   2.3. Matrix Approach .............................................................. 51
   2.3.1. Data storage and analysis ................................................. 51
   2.3.2. Statistical results ............................................................ 52

3. Measurement's Source of Errors 57
   3.1. IAS’ Error Sources ............................................................... 57
   3.1.1. Encoder’s geometrical error .............................................. 57
   3.1.2. Counter’s quantization error ............................................. 58
   3.1.3. Experimental test ............................................................. 60
3.2. Other Error Sources ................................................................. 66
  3.2.1. Clock stability ................................................................. 66
  3.2.2. Electrical noise ............................................................... 67

4. Experimental Tests ............................................................. 69
  4.1. Experimental Test Rig - 1 ..................................................... 69
    4.1.1. Motor behaviour .......................................................... 71
    4.1.2. Torsional Laser Vibrometer ......................................... 75
    4.1.3. IAS compared to Acceleration ...................................... 80
    4.1.4. Unbalance test ........................................................... 80
  4.2. Experimental Test Rig - 2 ................................................... 84
    4.2.1. Measurements ETR2 ..................................................... 84
    4.2.2. Characteristic orders in the IAS spectrum ....................... 90
  4.3. Experimental Test Rig - 3 ................................................... 98
    4.3.1. Dynamic characterization .............................................. 98
    4.3.2. Test configuration ..................................................... 104
    4.3.3. Acceleration ............................................................ 107
    4.3.4. Voltage and Current .................................................. 108
    4.3.5. IAS analysis ............................................................ 109
    4.3.6. Power supply unbalance .............................................. 125
  4.4. Measurements at Nidec ASI S.p.A. .................................... 128
    4.4.1. CR 900 X4 ............................................................... 128
    4.4.2. CT 560 Y4 ............................................................... 134

5. Conclusion ................................................................. 137

Appendices ................................................................. 139

A. Maintenance Terminology ............................................... 139

B. Nidec ASI S.p.A ............................................................ 143

C. Incremental Encoder ........................................................ 145

D. IaSaT - Instantaneous Angular Speed Analysis Tool ............. 147

References ................................................................. 149
Preface

This research is focused on the condition monitoring of electrical machines, thanks to the sponsorship of Fondo Sociale Europeo (and Regione Friuli Venezia Giulia) and to the collaboration with Nidec ASI S.p.A., an electrical motor company. The long term purpose of this study is to monitor electrical and mechanical defects at the same time, with a single piece of hardware. A difficult challenge is doing this with varying load and speed. Many measurements could be adopted for monitoring an electrical machine, for example: the vibration, the voltage, the current, the acoustic emission, the thermography and the oil analysis. Comparing different techniques from the bibliography, the Instantaneous Angular Speed (IAS) has the potential to be a great solution for these challenges.

Chapter 1 introduces basic principles about the maintenance of an electrical machine. Frequently machine unscheduled downtimes are caused by bearing faults, and rotor/stator faults. Precision Maintenance tries to avoid fault generation, by keeping the installation parameters as close as possible to the manufacturer’s suggested values. In this way, the unbalance and the misalignment are kept low and bearings will have a longer life. Despite that, monitoring systems are needed when the machine is very important for the plant (cost, safety). In this chapter, the electrical machine’s behaviour is also examined. Induction electrical machines are chosen for this research. The particularity of this kind of electrical machines is the slip effect. The current flowing into the stator generates electromagnetic excitations that can be seen in the measurement’s signal. A review of the excitation frequencies is reported in the chapter. In the last section, characteristic fault frequencies (from mechanical and electrical sources) are collected.

Chapter 2 presents the IAS measurement and its signal processing. The IAS is the measurement of the shaft rotating speed in order to visualize what’s happening during a single or in multiple turns. There are many measurement methods which are based either analog to digital conversion or which use counters. Analog to digital methods use a standard data acquisition board. Counter methods have to use specific hardware that is more expensive, but with less data to store. Counter boards have a clock of over 100MHz, improving the measurement’s resolution. In this research, the counter method is used, combined with the Elapsed Time (ET) counting technique: the IAS is obtained measuring the time between two pulses of an encoder. The rising edge of the square wave starts the counter and the successive rising edge stops it. The number of timebase ticks times the clock’s period equals the total time elapsed. The rotational angle between two pulses is a constant (except the geometrical error) and it is calculated as: 360° over number of encoder’s divisions. The IAS is calculated as: Δ angle over total time elapsed. It follows that, the IAS information is directly correlated with the angular position. The measurement’s accuracy is analysed, finding the relationships with the speed and the encoder’s characteristics. The FFT processing, and the other signal processing techniques are described.

Chapter 3 describes the encoder system. Its output signal is acquired with an oscilloscope and with the counter board. The signal’s differences are highlighted. In this chapter, the measurement’s source of errors are listed: the encoder’s geometrical error, the counter’s quantization error, the clock stability and the general electrical noise.
Chapter 4 collects all the experimental tests done during the PhD research. Three experimental test rigs are shown and two measurements in Nidec ASI S.p.A. are reported. Note that the experimental test rigs are designed and built in the Universita degli Studi di Trieste during the three years of the PhD.

Experimental Test Rig 1 (ETR1) is used to understand: the electrical motor’s behaviour with varying speed; the difference between the IAS and the speed acquired with the Torsional Laser Vibrometer; the difference between the IAS and the acceleration signal measured with an accelerometer located on the motor’s stator; the effect of the unbalance in the IAS measurement.

Experimental Test Rig 2 (ETR2) allows to examine: the load effect on the IAS measurement; the magnetomotive force harmonics; the slip and the rotor effects.

Experimental Test Rig 3 (ETR3) is designed in order to detect the Inner Race Bearing Fault (Ball Pass Frequency Inner - BPFI) with varying load. The acceleration, the voltage and the current are compared with the Instantaneous Angular Speed. The motor is also tested with an unbalanced power supply.

The two measurements in Nidec ASI S.p.A shows how the IAS measurement could be implemented in an industrial machine larger than the one tested in the laboratory.

This research presents the pros and cons of the IAS measurement, highlighting the capability of: detecting BPFI bearing fault; feeling the load variations owing to the brake system (a synchronous generator); measuring the Fundamental Train Frequency of an healthy bearing; detecting unbalance in the rotor. The IAS’ main advantage with respect to the acceleration signal is that BPFI harmonics remain fixed when the load changes. An automatic fault detection system could be set at a specific order, without the necessity of following the peak due to load and speed variations.
1. Introduction

1.1. Maintenance of Electrical Machines

This section deals with the concept of monitoring the condition of rotating machinery to determine its present health. In an industrial plant, a specific maintenance approach should be adopted for every piece of equipment. The machinery’s importance (e.g. cost of unplanned shutdown, safety) drives the choices of a maintenance program. For example, the Reliability Centered Maintenance (RCM) (Fig. 1.1), described in Appendix A, divides the machines into four groups:

- **Reactive Maintenance**: a maintenance task is performed after a failure has occurred;
- **Preventive Maintenance**: a maintenance task is done before a fault occurs (Planned Maintenance (PM));
- **Predictive Testing & Inspection (PT&I) Based Maintenance**: determines the condition of in-service equipment in order to predict when the maintenance should be performed. It requires online monitoring (Predictive Maintenance (PdM), Condition Based Maintenance (CBM), Condition Monitoring (CM));
- **Proactive Maintenance**: tries to understand the machinery behaviour and takes actions in order to avoid further failures.

The reasons for carrying out one of the above mentioned approaches are given below [35]:

- **Eliminate Unnecessary Disassembly**: Any time a machine is tampered with, there is a possibility that it will be damaged. A machine that is exhibiting no sign of wear or faulty operation should be left alone to do its job for as long as possible.
- **Reduce Unscheduled Downtime**: If a particular machine is beginning to exhibit signs of incipient failure, it is possible to schedule its repair during a convenient time (i.e., during a planned shutdown). Provision can be made to ensure that the proper replacement parts, tools, equipment, and manpower will be available at the appointed time.
- **Avoid Wrecks**: By following the condition of each machine as it ages, one can predict the onset of many destructive modes of failure before they occur.
- **Reduce Insurance Costs**: Lost production insurance and liability insurance can possibly be reduced by demonstrating that a plant’s monitoring system can successfully reduce machine failure.

The goal of a maintenance program should be fewer unexpected failures in the plant, maximum running time between shut downs, and the elimination of recurrent failures. These objectives should be reached with minimum capital investment. In Appendix A, maintenance related definitions and references are reported. When a machine is fundamental for an industrial plant, a monitoring system is adopted in order to track the behaviour of the machine, applying the so called PT&I Based Maintenance. In this scenario, the Instantaneous Angular Speed (IAS) could be useful because it has specific properties that will be described and discussed in the following chapters.
1.1.1. Projecting maintenance

The ability to find as many impending machinery failures as possible (without deactivating or opening the machine unnecessarily) requires a hardware/software system able to collect data from many sources. This kind of system needs the selection of transducers, their locations, the amount of data to collect (for trending features), the signal’s thresholds and limits. This could be enough for a Predictive Maintenance program, when the system’s output should suggest when to stop the machine. But, for Proactive Maintenance, the monitoring program should provide an output with enough historical data to correlate the causes and effects of failure. Although it is beneficial to capture data on a piece of machinery and know that, for example, a particular bearing is failing for the third time in a year, it is certainly more useful to know why the bearing regularly fails.

In [35], the answers to common questions are reported: which machines should be monitored?, who should decide which machines should be monitored?, how often should a machine be monitored?, what non-vibration parameters should be measured?, how are baseline criteria chosen?, under what operating conditions should readings be taken?, where should the vibration readings be taken?, what kind of vibration transducer should be used?

Continuous monitoring programs generally involve machines that meet one of the following three criteria:

1. The machine is critical to production
2. The machine is extremely costly to replace
3. Failure of the machine could easily result in injury or loss of life

Periodic monitoring programs are sometimes carried out on machines meeting the above criteria, but more often include the following, less critical criteria:

1. The machine is fairly costly to repair or replace
2. Failure of the machine may cause increased production costs or reduced plant output, but not necessarily a complete plant shut down
3. Machines with a poor operating history

The component replacement cost, the cost of lost production on a machine, and, probably most importantly, the potential for damage to the rest of the process machinery are very important in establishing the importance of the machine. Also the probability of danger to plant personnel and local residents must be taken into account. The question of how costly a machine is usually depends on the size of the capital budget of the facility. Lost
production cost is a function of the value of the product in the marketplace and the effect a given machine has on the volume of production of the product. An analysis of how much of the total production will be lost due to the downtime of a particular machine must be estimated. A machine becomes less critical if there is a spare machine (twin machine) in the industrial plant. The decision as to which machines should be monitored and the method of monitoring those machines (whether continuously or periodically) should not be made by the maintenance manager or the local vibration expert. This is a decision that must involve process, operating, and corporate marketing personnel as well. Such a priority number might well be calculated as:

$$\text{Priority} = \text{criticality} \times \text{reliability}$$

where criticality is assigned as a function of how necessary the machine is to the attainment of the production goals and reliability equals the inverse of the probability of failure of the machine when operated at the necessary operating conditions multiplied by the amount of time required to repair or replace the machine (i.e., time to replace / probability of failure).

1.1.2. Monitoring settings

The monitoring of a machine could be:

- continuous: very important machines in the plant
- periodic: scheduled every a certain time (period, interval)

Continuous monitoring is reserved only for extremely costly pieces of equipment. The data acquisition setting of a continuous measurement system is easier then a periodic one because the monitoring schedule for a given machine depends on the operating history, design, and duty cycle of the machine. This interval is, at best, a guess that is highly tempered by the cost and difficulty of monitoring each location to be measured. Any monitoring interval short of continuous monitoring incurs the risk that an unpredictable failure of some kind will destroy the machine between monitoring intervals.

The most common properties measured are pressures, temperatures, flow rates, shaft speeds (usually obtained from the vibration measurement), and power consumption (measured in amperes or watts at the motor). The degree of accuracy to be obtained is a function of the criticality of the measurement. Some of the most recent vibration monitoring devices employ a pickup that can measure temperature and acceleration simultaneously. The only parameters that should be measured are those that are nonintrusive to the manufacturing process. When deciding what parameters to use for monitoring a given machine, it has to bear in mind that gathering too much data will result in a waste of memory and an unwieldy database. The manufacturer of a particular machine should provide correct advice on the monitoring of parameters.

Another monitoring setting is the threshold value. There are three ways commonly used to obtain baseline vibration data:

- establish an arbitrary plant-wide level of about 2.5 mm/sec rms;
- use filtered vibration readings at the measuring locations of each machine and assume that these levels are normal. A 3 dB increase (doubling) in the level in any frequency band will constitute an alarm state, and a 5 dB increase (tripling) will constitute a severe warning level. After a few monitoring periods have gone by, it is wise to reevaluate the baselines in light of the data. Computer programs exist to calculate the means and standard deviations of the gathered data to set statistically improved baselines.
use detailed narrow-band spectrum analysis of the machine. This will allow a skilled analyst to consider each of the mechanical components of the machine (which generates unique frequency components) separately. This is infinitely better than measuring an overall vibration level and hoping that it represents all the critical components (bearings, couplings, gears, rotors, etc.) of the machine. Each frequency peak must be examined separately and its amplitude level used to determine whether its forcing mechanism is occurring at acceptable levels of vibration. If not, the possibility of incipient machine failure must be considered and a detailed diagnosis of the problem carried out.

Nidec ASI S.p.A established vibration limit levels according to [5], Fig. 1.2. In bibliography other limits and information are reported, [67].

If a machine operates at constant load and speed, thresholds and data acquisition settings can be set and kept fixed (except variations due to summer and winter operation, if they affect the system’s behaviour). Instead, with varying load and speed, these parameters should be adapted to the specific working condition. In this case, an order tracking procedure is suggested, obtaining vibration data in order domain.
The solution presented in this thesis, acquires the signal (Instantaneous Angular Speed) using a constant angular sampling (encoder divisions), so it is suitable to operate at different speed and loads.

Another problematic selection is the sensor type: which one is the best for a specific application? accelerometers? proximiters? velocity pickups?

For rotating machines, vibration readings are generally taken at each bearing-housing system in three orthogonal directions. This information is useful because the vibration of the rotating equipment is transmitted through the bearings. This transmission is more pronounced with rolling element bearings than sleeve bearings. As one gains experience in monitoring particular pieces of equipment, it becomes possible to reduce the number of data points on a given machine without significantly reducing the probability of finding an incipient fault in time to deal with it.

Sleeve bearings can use proximeter sensors. They measure the displacement of the shaft in respect to the mounting location. It should be noted, however, that the frequency range for which valid information can
be obtained is quite low, and the proximeter’s mounting should not have structural resonances in the sensor’s measuring range.

Velocity pickups are popular because they weight low, middle and high vibration evenly, Fig. 1.3. However, they have some very basic problems. Since velocity pickups operate above their natural frequency (which typically is approximately 10Hz), the sensitivity of the pickup drops quite radically below 10Hz. In addition, the velocity pickup up tends to be sensitive to cross-axis affects. That is, if the pickup is mounted in the vertical direction, the output could be affected by extreme vibration in the horizontal or axial direction. [70].

Accelerometers have the advantage of having adequate sensitivity over a wide range of frequencies. The low end of frequency response of a typical piezoelectric accelerometer is 1-3 Hz and the upper end tends to range between 5 and 20 kHz. For this reason, an accelerometer is often the preferred device to use. Certain problems can arise when accelerometers are used to measure low-frequency signals. These problems can be solved by integrating the signal (by analog or digital means) and reading out the vibration data in terms of velocity units.

Instantaneous Angular Speed (IAS) uses an encoder system directly connected to the shaft, so only one transducer is necessary. The data stream is composed of only one signal channel. Another point is the little amount of data to handle for each acquisition (0.2 MB/s). In Sect. 2.1 the IAS’ properties will be shown.

Figure 1.3.: Sinusoidal acceleration and displacement amplitude as a function of frequency for a fixed velocity amplitude of 1 mm/s rms
1.1.3. Considerations

In this section, global considerations are collected from the conferences attended during the PhD research. The issue of the measurement data storage is very important due to the large amount (GB) of data stored during continuous monitoring. There are some railway companies in Europe that have implemented this kind of system using: continuous monitoring, automatic pattern recognition, information coding. A secondary, but not less important problem is connected to the data visualization and analysis: *you have the data but you don’t have time or resources to analyze it* - they say. Often a measurement is seen a few months late in respect to the fault instant. In the market there are many software packages for maintenance planning: there is software for historical fault storage and software for the measurement and analysis of a machine, but there is no tool that allows management to say when and how to do it. The history of a machine is very important in a maintenance program: the Equipment Maintenance Log must be filled after each maintenance task and a Work Log should also be compiled in order to have a complete machine situation.

Usually the measurement of a single quantity is not useful and a multi channel system should be used in order to take into account, for example, the environmental interaction with the machine (seasonal weather change, dusty surroundings). A special case is the Instantaneous Angular Speed IAS monitoring because with only one sensor, multiple information could be extracted.

In industry, significant maintenance improvements are obtained when attention is focused on a single specific fault. It is not possible to study a machine’s behaviour using only one single global measurement. The goal of a maintenance program is to consider a machine as a single entity, with an own single life: two machines are the same in the seller’s catalog, but are different in the plant, from the time of first installation. Also the measurement system should be periodically checked, such as sensors’s calibration (trending?) and health.

In general, the recent software developments are focused on the integration of CMMS (Computerized Maintenance Management System) and ERP (Enterprise Resource Planning) software. Information should be personalized for a specific viewer (manager or technician).

Nowadays, many hardware and software products are taken from the entertainment market because here the development is very fast. There are solutions using augmented reality (Google Glass) and 3D plant views (game stuff).

But these entertainment solutions are not indicated for industrial applications due to the harsh environment (noise, vibration, dust, heat) and the market knows it so the industrial buyer is waiting for a more industrial oriented hardware solution (they don’t want iPads!). Also the continuous software update is not well seen by the industrial player. The intellectual property must be guaranteed during migration from paper to electronic copy and web storage.

Another point is the traceability of a component: RFID and Barcode solutions have been implemented in many companies. In this way an Equipment Maintenance Log could be electronically updated day by day, allowing the synchronization of many databases (maintenance, buy and sell, production, design).
1.2. Electromagnetic Excitations in Induction Machines

1.2.1. Introduction

This research is focused on condition monitoring of electrical machines, thanks to the collaboration and sponsorship of Nidec ASI S.p.A. (Monfalcone plant, Italy). A description of the company can be found in Appendix B. Nidec ASI S.p.A. offers a wide range of electric motors and generators. After a comparison based on the market, induction machines were selected for this research, Fig. 1.4.

**Induction motor, how it works**  In an induction motor, the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding, Fig. 1.5 1.6. An induction motor therefore does not require mechanical commutation. Three-phase squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical, Fig. 1.7. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. A basic description of the induction motor can be found in [58].

![Figure 1.4.: Nidec ASI Induction Machines: a) Series W/N/CB, Power rating: 150 - 25,000 kW, 200 - 33,000 HP, Voltage: up to 15 kV; b) Series CR, Power rating: 150 - 25,000 kW, 200 - 33,000 HP, Voltage: up to 15 kV; c) Horizontal or vertical mountings available](image1)

![Figure 1.5.: Inherent slip - unequal rotation frequency of stator field and the rotor](image2)
Figure 1.6.: A three-phase power supply provides a rotating magnetic field in an induction motor

Figure 1.7.: Three-phase squirrel cage induction motor
1.2.2. Electrical parameters

Table 1.1 shows the principal electrical parameters of an induction motor. This nomenclature will be used in the next sections and chapters and it is represented according to reference [33].

<table>
<thead>
<tr>
<th>$f$</th>
<th>Fundamental frequency</th>
<th>$s$</th>
<th>Slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>Pole pair number</td>
<td>$m$</td>
<td>Number of phases</td>
</tr>
<tr>
<td>$k, g$</td>
<td>Ordinal numbers</td>
<td>$\nu$</td>
<td>Harmonic order</td>
</tr>
<tr>
<td>$\nu_+$</td>
<td>Harmonic order (forward)</td>
<td>$\nu_-$</td>
<td>Harmonic order (backward)</td>
</tr>
<tr>
<td>$R$</td>
<td>Rotor slot (bars)</td>
<td>$S$</td>
<td>Stator slot</td>
</tr>
<tr>
<td>$F_{m\nu}$</td>
<td>MMF Amplitude</td>
<td>$\theta_s$</td>
<td>Angle (stator ref)</td>
</tr>
<tr>
<td>$o_\nu$</td>
<td>Order in IAS spectrum</td>
<td>$f_r$</td>
<td>Frequency in current spectrum</td>
</tr>
<tr>
<td>$sk$</td>
<td>Skewness</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$P = 2p$  
Poles
$
\omega = 2\pi f$
Angular frequency

$n_s = \frac{f}{p}$
Synchronous speed

$n_{s\nu} = \frac{f}{(\nu p)}$
Synchronous speed for $\nu$th harmonic

$n_m = (1 - s)n_s$
Mechanical speed

$\tau_s = \frac{1}{n_s}$
Synchronous speed period

$\tau_m = \frac{1}{n_m}$
Mechanical speed period

$n_{sl} = n_s - n_m$
Slip speed

$s = \frac{n_{sl}}{n_s}$
Slip definition

$s_f = psn_s$
Slip frequency

$s_{\nu} = 1 - \nu(1 - s)$
Slip for $\nu$th harmonic

$f s_{\nu} = f[1 - \nu(1 - s)]$
Slip frequency for $\nu$th harmonic

$\nu = 2mg + 1$
the order of the space harmonics

$\mu = \frac{gs_\pi}{p} + 1$
the order of the rotor space harmonics

1.2.3. Theory of the development of flux in the air gap

The main task in creating electromechanical energy conversion by asynchronous machines is to get a rotating sinusoidal magnetic field with pole number $P = 2p$. In machines of standard construction, the magnetic flux in the air gap is induced by the current flowing through the conductors in the slots. Slotting has two consequences. First, the Magneto Motive Force (MMF) is staggered round the circumference, and consequently the MMF wave has a strong harmonic content superposed on the fundamental. Secondly, the slots, in particular the open slots, break up the uniformity of the air gap round the circumference, and the gap, which represents almost the total reluctance of the magnetic circuit, will change periodically as the relative position of the stator and the rotor changes. The local maximum and minimum values of permeance correspond to tooth-faces-tooth and slot-faces-slot situations, respectively. The total magnetizing current of an asynchronous machine is supplied from the mains, and therefore the air gap is designed to be as small as possible. In this case, however, even the smallest deviation of the air gap from the shape of a cylindrical sleeve of uniform thickness will result in considerable relative distortion of air gap permeance. The eccentricity of the rotor and iron saturation will also give rise to permeance harmonics. The air gap flux density harmonics induce periodic
exciting forces which act on the mechanical system of the machine. Fig. 1.8 illustrates the generating process of exciting forces of electromagnetic origin. The rotor and stator are both slotted and operate in complex magnetic interaction. In order to comprehend the problem itself and then its solution, it is worthwhile following the process of how the flux density distribution is established in the air gap, as shown in Fig. 1.9, where the block diagram only outlines the infinite cycle without being readily suitable for the development of an algorithm for computation. In the stator of a symmetrical unsaturated three-phase machine (i.e., with identical phase windings of symmetrical arrangement, fed from a symmetrical mains supply of voltage $U_{sup}$ and free of harmonics, uniform and constant air gap), there is a symmetric current system of angular frequency $\omega$, assuming, for the time being, that only fundamental currents are present. This current lags on the voltage by a given phase angle. All three phase currents set up an MMF varying with time, staggered round the circumference, so in addition to the fundamentals of pole pair number $p$, space harmonics of pole pair number $\nu p$ will be produced as well. The alternating MMF established by the three phase windings make up a rotating MMF, but the permeance of the air gap is not uniform. It is altered by slotting, saturation and rotor position. The former is called the MMF wave, the latter, the permeance wave. All the MMF waves interact with the constant term of the permeance, and excite the stator fundamental wave and the winding flux density harmonics. The pole pair number of these equals the pole pair number of the MMF waves. In addition, all the MMF waves interact with each permeance wave, inducing further flux density waves of pole number and frequency equal to the sum or difference of the corresponding orders of the stator MMF and permeance waves. This infinite series of flux density waves,

$$\left( \sum_{\nu} b_{\nu} \right)$$

passing through the air gap, acts on the rotor winding (squirrel-cage), inducing in it voltages having identical order of harmonics. The induced voltages drive currents in the closed rotor circuit, depending on the impedance of rotor winding. This impedance is a function of, among others, the frequency, the number of turns (or, for squirrel-cage motors, the number of slots), the permeability of iron, the shape of the slots, etc. Owing to the rotor slotting, each of the above currents gives rise to MMF waves having mode number

$$\lambda \left( \sum_{\nu} \sum_{\mu} F_{m\nu\mu} \right)$$

that contains a theoretically infinite excitation number harmonics. As a result of interaction between the MMF waves and the permeance waves of the air gap, a new set of flux density waves is generated.

$$\lambda \left( \sum_{\nu} \sum_{\mu} b_{\nu\mu} \right)$$

Out of these flux density waves, those with order equal to that of the stator flux density waves ($\mu = \nu$) react on the corresponding stator flux density harmonics (armature reaction). The remaining waves are called residual rotor flux density waves. These residual rotor fields induce voltage again in the stator windings, with frequency different from that of the network frequency. For these voltages, the stator circuit is virtually short-circuited via the supply network, and therefore currents determined by stator impedance $Z_s$, will flow in the winding conductors. Of course, each current component

$$\sum_{\nu} \sum_{\mu} i_{\nu\mu}$$

flowing in the stator windings gives rise to new MMF harmonics a part of which (when $\mu = \nu$) reacts on the residual rotor flux density waves, while the other part will constitute the residual stator flux density waves.
This process continues until the steady-state flux distribution is established in the air gap. It is unnecessary to determine all the theoretically infinite number of steady-state flux density harmonics and to take them into consideration in the calculation of the radial force. Even the most stringent requirements are satisfied by an analysis that neglects harmonic generation processes following letter \( B \), since the amplitudes of voltage harmonics induced in the stator windings are generally very small.

### 1.2.4. Radial force waves of electromagnetic origin

The interaction of rotor and stator waves is really important. The magnetic forces can be expressed in the following form

\[
p_r(\alpha, t) = P_{mr} \cos(r\alpha - \omega_r t)
\]  

(1.1)

where

- \( p_r \) is the radial magnetic force per unit area (or magnetic pressure)
- \( \alpha \) is the angular distance from the origin of the coordinate system
- \( t \) is the time
- \( P_{mr} \) is the amplitude of magnetic forces
- \( \omega_r \) is the angular frequency
- \( r = 0, 1, 2, 3, \ldots \) orders of radial magnetic forces

The radial forces circulate around the stator bore with an angular speed \( \omega_r/r \) and frequency \( f_r = \omega_r/(2\pi) \). For a small number of stator pole pairs the radial forces may cause the stator to vibrate and produce acoustic noise. The extent of deformation and noise becomes excessive when the frequency of the exciting force \( f_r \) is close or equals to one of the natural frequencies of the machine. This coincidence which results in the phenomenon of resonance can occur under steady-state running condition at working speed but also in transient operation. If we look at the formula of angular frequency in the force wave equation, we find frequencies reported in Table 1.2.

The frequency of the exciting force is directly proportional to the speed of the machine. Therefore resonance may occur in the acceleration period in cases when the mechanical natural frequency of the machine in continuous operation is much lower than the frequency of the exciting force. In other words, the smoothly running machine might "roar up" during the acceleration period. This transient resonance may show up under other types of transient operating condition, like reversing, or in the generator braking mode of multiple-speed motors. Based on theoretical considerations and practical experience, the force waves classified as dangerous in terms of vibration or noise can be selected on the basis of their mode number and frequency. The low and medium power asynchronous machines have proved to be extremely rigid against force waves with mode numbers over 6. From experience, the following frequency ranges must be considered for asynchronous machines:

- for noise \( \quad 200 \leq f_r \leq 4000 \text{Hz} \)
- for vibration \( \quad 10 \leq f_r \leq 1000 \text{Hz} \)
Table 1.2.: Frequencies of radial magnetic forces produced by higher space harmonic $\nu = 1$ (fundamental time harmonic $n = 1$) in induction motors, [33].

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency [Hz]</th>
<th>Order (circumferential mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product of stator space harmonics $b_\nu^2$ of the same number $\nu$</td>
<td>$f_r = 2f$</td>
<td>$r = 2\nu p$</td>
</tr>
<tr>
<td>Product of rotor space harmonics $b_\mu^2$ of the same number $\mu$</td>
<td>$f_r = f \left[1 \pm k(R/p)(1 - s)\right]$ where $s$ is the slip for fundamental space harmonic</td>
<td>$r = 2\mu p$</td>
</tr>
<tr>
<td>Product of stator and rotor space harmonics $b_\nu b_\mu$ - general equations</td>
<td>$f_r = f \pm f_\mu$</td>
<td>$r = (\nu \pm \mu)p$</td>
</tr>
<tr>
<td>Product of stator and rotor space harmonics $b_\nu b_\mu$ - where $\nu = kS/p \pm 1$ and $\mu = kR/p \pm 1$ (the so called slot or step harmonics)</td>
<td>$f_r = f \left[k(R/p)(1 - s) \pm 2\right]$</td>
<td>$r = kS \pm kR \pm 2p$</td>
</tr>
<tr>
<td></td>
<td>$f_r = f \left[k(R/p)(1 - s)\right]$</td>
<td></td>
</tr>
<tr>
<td>Product of stator and rotor static eccentricity space harmonics $b_\nu b_\mu$</td>
<td>$f_r = f \left[2 + k(R/p)(1 - s)\right]$</td>
<td>$r = 1$</td>
</tr>
<tr>
<td></td>
<td>$f_r = f \left[k(R/p)(1 - s)\right]$</td>
<td>$r = 2$</td>
</tr>
<tr>
<td>Product of stator and rotor dynamic eccentricity space harmonics $b_\nu b_\mu$</td>
<td>$f_r = f \left[2 \pm (1 - s)/p + k(R/p)(1 - s)\right]$</td>
<td>$r = 1$</td>
</tr>
<tr>
<td></td>
<td>$f_r = f \left[(1 - s)/p + k(R/p)(1 - s)\right]$</td>
<td>$r = 2$</td>
</tr>
<tr>
<td>Product of stator and rotor magnetic saturation space harmonics $b_\nu b_\mu$</td>
<td>$f_r = f \left[k(R/p)(1 - s) + 4\right]$</td>
<td>$r = kS + kR + 4p$</td>
</tr>
<tr>
<td></td>
<td>$f_r = f \left[k(R/p)(1 - s) + 2\right]$</td>
<td>$r = kS + kR + 2p$</td>
</tr>
</tbody>
</table>
Figure 1.8.: The influence diagram of exciting force generation of electromagnetic origin

Figure 1.9.: The building-up of the air gap field in asynchronous machines
1.2.5. Electromagnetic torque components

The instantaneous torque of an electrical motor

\[ T(\alpha) = T_0 + T_r(\alpha) \]  \hspace{1cm} (1.2)

has two components:

- constant or average component \( T_0 \)
- periodic component \( T_r(\alpha) \)

The periodic component causes torque pulsation also called torque ripple. The torque ripple is caused by both the construction of the machine and power supply. There are three sources of the torque ripple coming from an electrical machine:

- cogging effect (detent effect), that is, interaction between the rotor magnetic flux and variable permeance of the air-gap due to the stator opening geometry
- distortion of sinusoidal or trapezoidal distribution of the magnetic flux density in the air gap
- the difference between permeances of the air gap

The cogging effect produces the so-called cogging torque, higher harmonics of the magnetic flux density in the air gap produce the field harmonic electromagnetic torque, and the unequal permeance produces the reluctance torque. The causes of torque pulsation coming from the supply are:

- current ripple resulting, for example, from PWM
- phase current commutation

The theory of higher harmonic torques of induction machines due to stator and rotor slots have been developed by main authors. [41] explains that any induction motor may be imagined as a series of mechanically coupled asynchronous and synchronous motors having a different number of poles. An asynchronous torque is created if a certain stator MMF harmonic of the order \( \nu p \) produces in the spectrum of the rotor MMFs a harmonic of the same order \( \nu p = \mu p \). A synchronous torque is produced if the spectra of the stator and rotor MMF harmonics contain harmonics of the same order \( \nu p \) and if the rotor harmonic of this order is produced by a stator harmonic of another order \( \nu p \neq \mu p \).
1.3. Faults in Electrical Motors

Induction motors are frequently used in industries and can be one of the most important components of a system. The maintenance of this equipment is very important from a business and a safety point of view, so the electrical machine reliability has been an hot topic in industry for decades. Three mayor surveys were done in order to classify the major damages:

- 1983 by the Electric Power Research Institute (EPRI), project performed by General Electric (GE)
- 1985 by the Institute of Electrical and Electronics Engineers, Inc.(IEEE)
- 1995 by the Institute of Electrical and Electronics Engineers, Inc.(IEEE)

These surveys are published in [4]. Other recent studies confirm the results of former surveys, such as [60, 25, 26]. Other interesting surveys are in [83, 84, 43, 85, 23, 24, 1, 2, 3, 25]. Bearings and stators are the components where improvement of maintenance and redesign programs may most significantly increase motor reliability. Table 1.3: note that the most frequently failing components are ground insulation (18.5%) and sleeve bearings (9.7%), followed by ball bearings (4.9%), [7].

The previous studies show that inadequate maintenance and poor installation/testing are significant causes of failures, Fig. 1.10. On-line condition monitoring technologies and Precision Maintenance ([71, 74]) are proved to improve the motor reliability. For instance, motor bearing failures would be significantly reduced if the driven equipment is properly aligned through the operative life regardless of the loading conditions. Thanks to the collaboration between Nidec ASI S.p.A and Universita degli Studi di Trieste, a confirmation of this failure distribution is obtained: a statistical analysis is done using the service department information and the result is plotted in Fig. 1.11

1.3.1. Fault diagnosis techniques

Measurement techniques for fault detection are based on different measurement approaches: stator current measurement, vibration measurements (acceleration, velocity, displacement) as well as the method proposed in this work, the Instantaneous Angular Speed Analysis.

MCSA - Motor Current Signature Analysis the stator current is used as diagnostic signal: "stator current is the most used diagnostic signal in the industrial applications" [34], since it enables for noninvasive diagnostic and does not require the use of additional probes. A related problem during field measurements is the exposure to live parts. This may result in exposing the persons involved in the test set-up to electrical shock or arc-flash hazards, [30]. A review of MCSA diagnostic techniques is reported in [54, 21]. MCSA is not always reliable for bearing fault detection [17], since the amplitude of fault signatures in the current signal is very low, except in some dedicated operating conditions. In [34] the most common algorithms applied to MCSA are reported. There is an inverse relationship between the fault detection ease and the importance to the user of that fault detection. In fact, there are dozens of papers published on broken rotor bars and only two

<table>
<thead>
<tr>
<th>Failure</th>
<th>Percentage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearings Damaged (lubrication, misalignment, unbalance)</td>
<td>41</td>
</tr>
<tr>
<td>Stator Faults</td>
<td>37</td>
</tr>
<tr>
<td>Rotor Faults</td>
<td>10</td>
</tr>
<tr>
<td>Other faults</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 1.10.: Common reasons for bearing failures. Most of the known failures could be avoided if a proper bearing diagnostic and supervision system was in place, if the measurements which such a system provides are interpreted correctly, [42]

Figure 1.11.: Fault distribution Nidec ASI S.p.A.
or three on the use of MCSA for bearing faults detection, in spite of several studies that show bearing faults to account for almost 50% of induction motor failures as opposed to around 10% for rotor cage problems, [21].

**Vibrations** Many faults can be detected using acceleration, velocity or displacement sensors. Many books explain how to implement a condition monitoring system [62. 90. 70. 89]. Angular Resampling, Envelope Analysis and Cyclostationarity are the common techniques used in order to remove speed fluctuations, emphasize the presence of a fault and find a signal that varies cyclically with time. Sometimes the main problem is the transfer path of the vibration signal through the machine walls.

**IAS - Instantaneous Angular Speed** Some work has been done recently in order to show the capability of Instantaneous Angular Speed (IAS) to detect bearing faults [64. 27] and broken rotor bars [18. 8]. The IAS measurement is very informative for low speed and high radial load situations, but can also be applied for higher speed motors with a counter with high counting frequencies [76]. A common method used to acquire the IAS is through an incremental optical encoder and a counter board in order to measure the time elapsed between two rising edges of the encoder’s signal. In this way, the angular information is directly acquired. In a previous research, acceleration and IAS were compared [75] and the slip effect due to Induction motor behaviour was detected. In this work, the behaviour of the electrical motor is explained from the IAS point of view. The aim is to perform condition monitoring tasks using only the encoder connected to the rotor.

**Other techniques** Other techniques are used in industry in order to detect a fault in a machine, [70]: the airborne/structure borne ultrasound emission, the oil debris analysis, the electrical partial discharge, the monitoring of component’s thermal emission. These techniques are not discussed in this thesis.

### 1.3.2. Monitoring a machine

The FFT spectrum of a certain measurement’s signal is usually studied when a machine is in a faulty condition or during a continuous condition monitoring task, [70]. Faults manifest themselves increasing a specific frequency/order amplitude related to the system’s mechanical or electrical characteristics, Fig. 1.12. In rotating machines, often there is a modulation of the signal due to the shaft revolution: for example, the Inner Ring bearing fault shows a typical modulation at 1x rpm frequency. This modulation is represented as sidebands in the FFT spectrum.

In an electric motor, noise and vibration are related to the excitation forces produced by the electromagnetic field present in the stator and rotor of the motor. The behaviour of a motor can be affected by the variation of these fields due, for example, to the presence of an inverter (e.g. the switching frequency can be seen in the vibration spectrum), by a grid variation [29. 47] or by the motor’s design. Thus, the healthy induction motor also has a specific spectrum signature when there are no faults [44. 37]. In bibliography [88. 81. 33. 86. 41], different analytical formulas of the electromagnetic forces are reported. In the next section these main frequencies are summarized. These can be found in the current, vibration and IAS spectra.
New order?

New order with sidebands?

Figure 1.12.: How faults manifest themselves in the spectrum

Figure 1.13.: Typical faults and corresponding orders: a) eccentric rotor; b) bent shaft; c) angular misalignment; d) parallel misalignment
1.4. Characteristic Fault Frequencies in Induction Machines

Nowadays, there are no standardized or unified failure classifications in electrical machines, and this can be done by using different criteria, such as the origin of the failure (mechanical, electrical, hydraulic, etc.), the element of the machine (stator or rotor) where the failure occurs, and so on, [81, 87]. Reference [20] reports a complete bibliography on Induction Motors Faults Detection and Diagnosis up to December 1999.

1.4.1. Electrical faults

Stator, winding failures

These failures can occur inside the stator or in the supply system. Usually they are related to the winding insulation and the short-circuits may be located between:

- adjacent turns
- coils of the same phase
- phases (the machine stops)
- one phase and the earth (the machine stops)

Another cause is the open circuit of a phase. The detection of shorted coils is based on detecting frequency components $f_{sc}$ given by the equation 1.3 in current spectrum, [34].

$$f_{sc} = \left(k \pm n \cdot \frac{(1-s)}{p}\right)f \quad k = 1,3,5,\ldots \quad n = 1,2,3,\ldots$$

Another author [70] suggests the detection of 2x supply frequency $f$ in vibration spectrum, and the defect is called "loose iron".

Rotor, broken bar damages

Failures of rotor bars in squirrel cage induction motors generate a variation in the magnetic air-gap field. This variation produces sideband harmonic components at frequency $f_{brb}$ around the fundamental supply frequency component $f$, and also near other harmonics caused by not ideal winding distribution (current spectrum).

$$f_{brb} = \left((1-s)\frac{k}{p} \pm s\right)f \quad k/p = 1,3,5,\ldots$$

$$f_{brb} = (1 \pm 2ks)f \quad k = 1,2,3,\ldots$$

From reference [19], broken rotor bars can be found in current spectrum as Eq. 1.6 and in vibration spectrum as Eq. 1.7.

$$f_{brb} = f \pm 2p(n_s - n_m)$$

$$f_{brb} = n_m \pm 2p(n_s - n_m)$$

From reference [21], Eq. 1.8 (current spectrum).

$$f_{brb} = f \left[k \left(\frac{1-s}{p}\right) \pm s\right] \quad k/p = 1,5,7,11,13,\ldots$$

The amplitude of the left sideband frequency component is proportional to the amount of broken rotor bars. The position of the broken bar is very important in the detection: the frequency component $f(1 - 2s)$ does not
exist if broken bars are electrically $\pi/2$ radians away from each other. The rotor should be considered healthy when the amplitude of these sidebands is smaller than 50dB in respect to the fundamental supply frequency. Loose rotor bars are indicated by 2x supply frequency $f$ sidebands surrounding the Rotor Bar Pass Frequency (RBPF = number of rotor bars $R \times$ rpm) frequency and/or its harmonics in vibration spectrum. Other interesting references about broken rotor bars are [15, 16].

**Phasing problem (loose connector)**

Phasing problems due to loose or broken connectors can cause excessive vibration at $2f$, surrounded by $1/3f$ sidebands, [70].

**Unbalanced line voltage**

The unbalanced line voltage causes vibration at the frequency equal to the double the line frequency $2f$. Forces due to unbalanced magnetic pull (UMP) are calculated in [59].

### 1.4.2. Mechanical faults

**Unbalance**

A perfectly balanced machine does not generate any frequency components in the vibration spectrum. In the real machine a minimum unbalance of the rotating parts will always exist. Standards guarantee the minimum quality of balancing for each kind of machine. Often a better and higher quality balancing of a system is suggested, but most of the time the balancing procedure is quite expensive.

**Static unbalance** is produced by nonhomogeneous distribution of mass in the rotor. This failure is detectable with the rotor stopped. The FFT spectrum will show a predominant 1x rpm frequency of vibration, with its amplitude proportional to the square of the rotational speed [70].

**Dynamic (Couple) unbalance** is produced by a nonhomogeneous longitudinal distribution of weights in the rotor. A predominant peak is present at 1x and the there is a $180^\circ$ phase difference between two bearings in the same plane (horizontal or vertical). There are two kinds of dynamic unbalance depending on the orientation of the main inertia axis.

**Misalignment failures**

Misalignment, like unbalance, is a major cause of machinery vibration. Precision Maintenance aims at perfect alignment and balancing, but flexible couplings and self-aligning bearings are still necessary in a real machine in order to compensate for errors. There are basically two types of misalignment between two pieces of equipment: Angular (Fig. 1.13(c)) and Parallel (Fig. 1.13(d)).

**Angular misalignment** the shaft centerline of the two shafts meets at an angle with each other. Typically, there will be high axial vibration at 1x rpm (angular) and 2x rpm (angular + parallel). A $180^\circ$ phase difference will be observed when measuring the axial phase on the bearings of the two machines across the coupling.
Parallel misalignment this misalignment generates two hits per cycle and therefore a 2x rpm peak will be seen in the radial vibration spectrum. Normally also a 1x rpm peak will be present due to angular misalignment. Also in this case a 180° phase difference is present between the coupling. When angular and parallel misalignment become severe, higher harmonics will be generated.

Eccentricity failures

Eccentricity problems can be divided in: mechanical eccentricity between two pieces of equipment and eccentricity of an electric motor. The former occurs when the centre of rotation is at an offset from the geometric centerline of a sheave, gear, bearing, motor armature or any other rotor. The maximum vibration amplitude occurs at 1x rpm of the eccentric component in a direction through the centres of the rotors [70].

In the specific case of electrical machines, the rotor eccentricity can result from many sources (design, tolerances, operating conditions eg. temperature variation) and consists in the rotor being positioned slightly off-center in the stator bore. This non-ideal condition generates in the stator current (MCSA) four different groups of frequencies.

Static eccentricity can be produced by stator ovality, or by a misalignment of the mounted bearings or the bearing plates. Since the rotor is not centered in the stator bore, the field distribution in the air gap is not symmetrical. This generates radial forces of electromagnetic origin, called UMP, at frequencies given by Eq. 1.9. This method monitors the behaviour of the current at the sidebands of the slot frequencies. This scheme has the advantage of separating the spectral components produced by an air-gap eccentricity from those caused by broken rotor bars, but it requires the knowledge of the machine construction (number of rotor bars $R$).

$$f_{ecc\text{ static}} = \left[ \left( kR \left( \frac{1-s}{p} \right) \pm \nu \right) \right] f$$  \hspace{1cm} (1.9)

Dynamic eccentricity may be caused by a bent shaft, mechanical resonances, bearing wear on movement.

In all these cases the rotation axis of the rotor does not coincide with its geometric center. The radial length of the air gap varies with time for each air gap position. Frequencies are generated at Eq. 1.10.

$$f_{ecc\text{ dynamic}} = \left[ \left( kR \pm n_d \left( \frac{1-s}{p} \right) \pm \nu \right) \right] f$$  \hspace{1cm} (1.10)

where $n_d$ is a positive integer.

Mixed eccentricity (radial air-gap eccentricity) is the combination of static and dynamic eccentricity. It causes characteristic sideband components in the current spectrum at Eq. 1.11. This method does not require the knowledge of the rotor slot number $R$ because it monitors the fundamental sidebands of the supply frequency, [82].

$$f_{ecc\text{ mixed}} = f \pm kn_m \hspace{1cm} k = 1, 2, 3, \ldots$$  \hspace{1cm} (1.11)

$$f_{ecc\text{ mixed}} = f \left[ 1 \pm g \left( \frac{1-s}{p} \right) \right] \hspace{1cm} g = 1, 2, 3, \ldots$$  \hspace{1cm} (1.12)

Another author [70] suggested the detection of $2f$ with pole pass frequency sidebands (it also appears at low frequency).

$$f_{ecc} = 2f \pm \left[ 2p(n_s - n_m) \right]$$  \hspace{1cm} (1.13)
**Axial eccentricity** appears when the eccentricity varies along the axis of the rotor. Therefore, the axis of the rotor is not parallel to the stator axis and has different eccentricity in each section of the machine.

**Damaged bearings**

If a bearing has been damaged, then characteristic frequencies appear as the function of the type of damage in vibration spectrum, [79, 80]. The bearing deterioration progresses through different stages:

- high-frequency vibration (500kHz), detection using acoustic emission sensors
- 20-60kHz, accelerometer sensor with enveloping techniques (gSE, SEE, PeakVue, SPM)
- 10-2000Hz, accelerometer sensor with FFT processing (discrete bearing frequency appears)
- random noise, the bearing is approaching its end of life

\[
\begin{align*}
  f_{outer \ raceway} &= BPFO = \left( \frac{N_b}{2} \right) n_m \left[ 1 - \frac{D_b \cos \beta}{D_c} \right] \\
  f_{inner \ raceway} &= BPFI = \left( \frac{N_b}{2} \right) n_m \left[ 1 + \frac{D_b \cos \beta}{D_c} \right]
\end{align*}
\]  

(1.14)

where the number of balls is denoted \( N_b \), their diameter is \( D_b \), the pitch or cage diameter is \( D_c \), and the contact angle is \( \beta \).

\[
\begin{align*}
  f_{balls} &= BSF = \left( \frac{D_c}{2D_b} \right) n_m \left[ 1 - \left( \frac{D_b \cos \beta}{D_c} \right)^2 \right] \\
  f_{cage} &= FTF = \left( \frac{1}{2} \right) n_m \left[ 1 - \frac{D_b \cos \beta}{D_c} \right] \\
  f_{rolling \ defect} &= 2 \cdot BSF = \left( \frac{D_c}{D_b} \right) n_m \left[ 1 - \left( \frac{D_b \cos \beta}{D_c} \right)^2 \right]
\end{align*}
\]

(1.15)

(1.16)

(1.17)

(1.18)

In current spectrum, these frequencies can be found around the fundamental supply frequency, [20],

\[
f_{bearing \ defect} = |f \pm g f_{bear}| \quad g = 1, 2, 3, \ldots
\]

(1.19)

**Load effect**

If the load torque does vary with rotor position, the current will contain spectral components which coincide with those caused by faulty conditions. In an ideal machine where the stator flux linkage is purely sinusoidal, any oscillation in the load torque at a multiple of the rotational speed \( gn_m \) will produce stator currents at frequencies of Eq. 1.20

\[
f_{load} = f \pm kn_m = f \left[ 1 \pm k \left( \frac{1 - s}{p} \right) \right] \quad k = 1, 2, 3, \ldots
\]

(1.20)

Since the same frequencies are given by Eq. 1.19 and Eq. 1.12, it is clear that when the induction machine operates with a typical time-varying load, the torque oscillation results in stator currents that can obscure, and often overwhelm, those produced by the faulty condition. Therefore, any stator current single phase spectrum based fault detection scheme must rely on monitoring those spectral components which are not affected by the load torque oscillations. However, broken bars detection is still possible since the current typically contains higher order harmonics than those induced by the load.
2. Instantaneous Angular Speed

2.1. Introduction

In rotating machinery, the Instantaneous Angular Speed (IAS) variations can provide a large amount of information about the health status of the machine. In fact, from the variation of the IAS during the machine loads’ cycle it is possible to identify defects and faults: for example, impacts can be detected as in the Sect. 4.4.1. The current work focuses on the estimation of the IAS through the Elapsed Time (ET) method, using a counter to measure the time elapsed between the pulses of an encoder. Various researchers are studying the IAS measurement’s limits, new signal processing methods and new industrial applications.

From a general point of view, the angular speed can be expressed as:

$$\omega = \frac{d\varphi}{dt}$$

(2.1)

The rotational speed information can be extracted from various measurement devices:

- the incremental encoder is the most accurate and precise system in the list. It keeps the angular information in respect to time when combined with Elapsed Time method. It requires a high-quality installation. Its working principle and characteristics are described in chapter 3
- the magnetic encoder Similar to the incremental encoder but the disk or the ring is made up of magnets.
- the phonic wheel Often found in industry. The geometric error is bigger than the encoder’s one. Inductive or Capacitive sensors are used to detect the passing of a tooth (or hole) under the sensing zone, generating a square wave signal.
- the zebra tape A black and white tape is printed and glued to a shaft, [66]. The geometric error depends on the printing quality and there are errors due to the presence of joints. Optic sensors are used to detect the color change. A square wave is generated.
- the torsional laser vibrometer A laser system is used to detect the shaft speed, [77]. An angular reference could be provided by an additive phase sensor (optical) that gives one pulse per revolution. The output signal is proportional to the shaft speed. The speckle noise is present.
- the resolver is a type of rotary electrical transformer used for measuring degrees of rotation. It is considered an analog device, and its digital counterpart is the rotary (or pulse) encoder. It requires a phase reference.
- the dinamo The output voltage is proportional to the speed, but the signal is affected by noise.

The speed measurement could be done using counter based methods or analog to digital based methods depending on the output signal and the hardware available. The incremental encoder, the magnetic encoder, the phonic wheel and the zebra tape usually have a square wave output signal, Fig. 2.1. Using these devices, the angular speed is practically achieved through the measurement of the elapsed time $\tau(\varphi)$ between two consecutive rising edges issued from the angular sensor describing the
angle $\Delta \phi$, resulting in an averaged angular speed $\bar{\omega}(\phi)$:

$$\bar{\omega}(\phi) = \frac{\Delta \phi}{\tau(\phi)}$$ (2.2)

Fig. 2.2 shows how the IAS measurement could be used in industry. A classification can be done by using different criteria:

- operating conditions: continuous, on demand
- installation: fixed, temporary
- counting method: analog to digital methods, counter methods
- domain: angle, order

Considering a continuous operating mode, sensors such as the encoder, the phonic wheel and the resolver are suggested, while for a measurement on demand, noninvasive methods are preferred. For example, the zebra tape could be applied at a shaft in few minutes or a laser measurement could be done by simply fixing its head on a tripod, aiming at the shaft and turning on the instruments. An encoder can be added to an existing machine using a pulley system, but errors could be generated by a nonperfect transmission or positioning. Another installation solution could be done using a magnetic ring, bolted to the shaft.

A machine’s behaviour can be seen in angle or order domains. The order domain is obtained applying an FFT processing at the signal in the angle domain. The signal coming from an incremental encoder with the ET counting method is directly correlated to the angle domain ($\bar{\omega}(\phi)$) and the FFT can be immediately applied. The signal from a laser system or an accelerometer must be angular re-sampled before the FFT processing [77, 75] in order to switch from the time to the angle domain. Many other processing techniques may be applied in both domains, giving specific information on the machine’s health.
Figure 2.2.: IAS implementation
2.1.1. Counter based methods

The study of timer/counter-based methods has dominated the development of angular speed measurement techniques. The timer/counter can be implemented in a form of hardware or software. These methods are conceptually either measuring an elapsed time between successive pulses or counting pulses during the prescribed time. Based on this fundamental principle, improvements have been made that result in methods with better accuracy and response time.

Three counting methods are presented in this section: the Elapsed Time (ET) method, using one counter, and the High-Frequency (HF) and Large-Range (LR) methods, using two counters. A comparison between these methods is reported in [77] and in the Sect. 4.1.1. The measurement principles are described below.

In the ET method the rising edge of the input signal of the encoder triggers the counting of the timebase ticks (Fig. 2.3). Since the timebase is of a known frequency, the frequency of the input signal can be obtained as:

\[ f_{\text{count}} = 80 \text{MHz} \]  
\[ \Delta t_{\text{count}} = f_{\text{count}}^{-1} = 1.25 \times 10^{-8} \text{s} \]  
\[ f_{\text{input}} = \frac{1}{n_{\text{count}} \cdot \Delta t_{\text{count}}} \]  
\[ f_{\text{input}} = \frac{f_{\text{count}}}{n_{\text{count}}} \]

The HF method generates a pulse train with a user-specified period, "measurement time" (Fig. 2.4), larger than that of the input signal but small enough to prevent counter rollover. The time length of this internal signal should be a multiple \( m \) of the internal timebase. The number of ticks \( n \) of the input signal is counted within the known period provided by the internal signal. Dividing the number of ticks by the known measurement time gives the frequency of the input signal.

\[ \Delta t_{\text{meas}} = m \Delta t_{\text{count}} \]  
\[ f_{\text{input}} = \frac{n_{\text{input}}}{\Delta t_{\text{meas}}} \]

The LR method provides the highest accuracy. The input signal is divided by a known value \( k \). The number of ticks of the internal timebase is counted over one logic-high of the divided down signal (Fig. 2.5). This gives the time of the logic-high, product of the number of ticks counted and the period of the internal timebase. This can be multiplied by 2 to get the period for the divided down signal (high and low time), which is a multiple of the input signal period. The input signal’s frequency can be obtained by inverting this period. The method simulates the averaging over a longer acquisition period and can also be used to measure signals with frequencies higher than the timebase.

\[ \Delta t_{\text{high}} = k \Delta t_{\text{input}} \]  
\[ f_{\text{input}} = \frac{k}{2n_{\text{count}} \Delta t_{\text{high}}} \]

In this research, the adopted encoder-counter system is formed of an optical incremental encoder and a high frequency counter. Among the different processing strategies [46] in this work the Elapsed Time (ET) method is used. With this approach there are as many measurement values as there are pulses/revolution of the encoder. The frequency of the counter and the number of pulses determine the resolution of the IAS estimates. The method is strictly correlated to the real rotational angle of the shaft, except the encoder’s tolerances. [9. 91. 64].
Figure 2.3.: Digital signal with respect to internal timebase (one counter for Low Frequency)

Figure 2.4.: Digital signal frequency measured with two counters (High Frequency)

Figure 2.5.: Digital signal frequency measured with two counters (Large Range)
2.1.2. Analog to digital methods

This category of angular speed measurement method has attracted little interest from researchers in the area of condition monitoring and control. This is mainly due to the large amount of data and relatively low acquiring speed of ADC compared with timer/counter-based methods. However, with the dramatic increase in memory capacity of computers and ADC speed, ADC-based methods are exhibiting their attractive benefits in terms of maximum use of resources of general-purpose data acquisition systems. In [46] are reported various IAS estimation methods. These methods do not require a specialised measurement hardware because they extract the angular speed from the logged data using many different efficient signal processing techniques. A review of the principal extraction techniques is reported in [68]. In some papers, the Instantaneous Speed is called Instantaneous Frequency and it has been an issue of intensive research due to its importance in a broad range of applications, such as communications, radars, speech processing, seismography, biomedical applications, etc. Summarizing, these estimation techniques can be grouped as phase differencing methods, signal modeling methods, phase modeling methods and time-frequency-representation methods.

Typical time-frequency domain(TFD)-based methods are: the Hilbert transform, the adaptive short-time Fourier transform(ASTFT), the Wigner-Ville distribution and its variants, the Chirplet transform(CT), the short scale transform, and wavelets. Other emerging interesting approaches include Hidden Markov Modeling(HMM) algorithms, Kalman filtering techniques, or methods formulated in Bayesian statistical terms. Another approach is the Energy Operator Separation Algorithm(EOSA) and its digital version(DES, Discrete Energy Separation Algorithm). Parametric approaches (eg. time-varying AR modeling) can be applied for the estimation of the instantaneous rotational speed, since the major advantage of parametric methods over frequency domain or time-frequency domain based methods, is their increased resolution.

In [28] is reported an auto-tacho method able to extract the IAS from acceleration signal.

Many authors combined the processing of square wave signals with ADC methods, [66]. Considering the experiment done during this PhD research and reported in Sect. 4.4.2. these methods would be interesting if applied at the output signal of a sinusoidal incremental encoder. Another solution is to adopt a frequency-to-voltage converter. This method converts the frequency of a square wave into a voltage signal. The voltage amplitude is proportional to the input frequency. The voltage signal is then acquired using an ADC system.

![Encoder's working principle](image)

Figure 2.6.: Encoder’s working principle
2.1.3. Incremental encoder

The encoder is an electro-mechanic device, converting angular position of its shaft into a digital electric signal. When connected to suitable electronic circuits and through proper mechanic link, the encoder is able to measure angular displacements, linear and circular movements and also rotational speed and accelerations, Fig. 2.1.

A collimated light beam is aimed against two radial reticles: a static and a moving reticle (disc). Light that can pass through both reticles drops on a group of phototransistors placed immediately beyond the static reticle. By using several slots (instead of only one) on both reticles, the resulting electric signal is rather strong and actually is the average of many lines of the rotating disc. In this way, the electric output is not so sensitive to small disc imperfections or to small spurious parts in the optic system. The working principle of the encoder is represented in Fig. 2.6.

In this research, an incremental encoder TEKEL TSW80P is used, Fig. 2.7. A description of the incremental encoder is reported in the Appendix C. In the experimental setups designed for this thesis (discussed in chapter 4), a bolt keeps the encoder’s case in position in respect to the motor’s stator.

![Encoder TEKEL TSW80P](image)

**Figure 2.7.:** Encoder TEKEL TSW80P

**Encoder’s accuracy** The accuracy of position measurement with rotary encoders is mainly determined by, [40]:

- the directional deviation of the radial grating
- the eccentricity of the graduated disk to the bearing
- the radial runout of the bearing
- the error resulting from the connection with a shaft coupling (on rotary encoders with stator coupling this error lies within the system accuracy)
- the interpolation error during signal processing in the integrated or external interpolation and digitizing electronics.
For incremental rotary encoders with line counts up to 5000, the maximum directional deviation at 20°C ambient temperature and slow speed (scanning frequency between 1 kHz and 2 kHz) lies within:

\[ \pm \frac{18^\circ \text{mech} \cdot 3600}{\text{Line count } z} \text{ [angular seconds]} \]  

which equals:

\[ \pm \frac{1}{20^\circ} \text{grating period} \]  

(2.12)

Heidenhain guarantees this system accuracy for its ERN 120, a standard incremental encoder. Another definition could be found in http://elcis.elcis-encoder.com where the unit of measure to define the encoder accuracy is the "electric degree". 360° electric degrees equal the mechanic degree of the shaft, necessary to give a complete cycle of the output signal, that is:

\[ 360^\circ \text{ electric} = \frac{360^\circ \text{ mechanic}}{N^\circ \text{ divisions}} \]

The division error is given by maximum percentual deviation (in electric degrees) of the nominal distance between two wavefronts on one channel or on different channels. The error in a rotating encoder is not cumulative, as it does not increase when the shaft rotates for more than one revolution. Standard encoders have a maximum division error of ±45° (electric), randomly measured between two wavefronts of different channels, while maximum error between two consecutive wavefronts of two channels is MAX ±25° (electric). Waveform symmetry stays between ±15 (electric).

In Table 2.1. the measured standard deviation of the geometric error for two encoders are shown, [45].

![Image of encoder precision diagram]

Figure 2.8.: The encoder precision

<table>
<thead>
<tr>
<th>Encoder</th>
<th>N</th>
<th>std((\Delta \varphi))</th>
<th>std((\Delta \varphi))/(\text{mean}(\Delta \varphi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVL 364</td>
<td>720</td>
<td>1.4e-5 rad</td>
<td>0.16 %</td>
</tr>
<tr>
<td>Heidenhain ERN 120</td>
<td>2048</td>
<td>7.3e-7 rad</td>
<td>0.024 %</td>
</tr>
</tbody>
</table>

**Encoder errors and proposed corrections** The IAS measurement errors and especially the geometrical encoder errors are discussed in chapter 3. Two methods for the encoder geometrical error correction are shown in the Sect. 2.2.3 and Sect. 2.2.4.
2.1.4. Encoder measurement

In order to establish the clock speed necessary to get a proper speed measurement with the Elapsed Time method, a comparison test with an high speed oscilloscope is conducted (LeCroy LC334 AM, 2GS/s-500MS/s). The motor’s tested speed is about 1450rpm. Fig. 2.9 reports the measurement of the encoder’s square wave with, overprinted, the simulated counter ticks at the trigger zero crossing level (2.08V). In the graphs, the colored vertical lines represent the gap between two clock ticks of the counter. The counter with a clock frequency of 1MHz cannot acquire correctly the rising edge of the signal. Higher speed counters are necessary in order to measure the Instantaneous Angular Speed. 25MHz and 80MHz are the suggested values. There is a sort of noise at ”Hi” level due to the effect of electronics, Fig. 2.10. A comparison between grid powered and battery powered electronics is presented. The noise at ”Hi” state does not change between the two configurations, instead, the rising edge changes with the discharge of the battery because the ”Hi” level voltage decreases. A grid power supply with low electromagnetic emissions must be adopted for a correct and reliable measurement. A particular attention must be put in a proper ground/shield configuration. The background noise is very sensitive to the ground loops.

Figure 2.10 shows four square waves between two pulses of the encoder. The pulses are not consecutive because the data from the oscilloscope is stored manually. An oscilloscope like Pico Scope series should be used in order to acquire few seconds of the signal (with an huge data storage). The rising edge is triggered at 2.08V and the intersection between the trigger threshold and the signal gives the time \( t_0 \); the second rising edge represents the end time of the counting for the IAS estimation, \( t_1 \). \( n_{enc} \) is the number of encoder’s divisions.

\[
rpm = \frac{60}{t_1 - t_0} n_{enc}
\]

In Fig. 2.10 there are red and blue circles that represent the data acquisition points of the oscilloscope at 500MHz. An interpolation is necessary in order to obtain a value as close as possible at the trigger threshold. The speeds calculated are reported in Table 2.2

<table>
<thead>
<tr>
<th>Speed</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed red</td>
<td>1510.3488 rpm</td>
</tr>
<tr>
<td>Speed green</td>
<td>1497.7146 rpm</td>
</tr>
<tr>
<td>Speed blue</td>
<td>1488.5501 rpm</td>
</tr>
<tr>
<td>Speed black</td>
<td>1494.0333 rpm</td>
</tr>
</tbody>
</table>

Table 2.2.: Speeds calculated from encoder’s signal

The motor runs at about 1497.6617rpm ±10rpm. Considering a counter of 80MHz (12.5ns), and taking the black cycle, the actual speed is 1494.0333rpm and the error is ±0.476rpm (±0.032%). Fig. 2.12 shows many theoretical configurations of different clock speed, encoder’s disc diameter and ticks precision. The absolute error has a quadratic relationship with shaft speed, while the percent error has a linear trend. Other graphs show that the encoder’s geometric accuracy must be very high and a bigger diameter allows a longer time between one rising edge and the successive, so the resulting total error is lower. Note that the same error is generated using a counter with 100MHz clock speed and an encoder with 100ppr and a counter with 1GHz and 1000ppr. The mechanical diagnostic equipment and the maximum order of interest drive the selection of the counter frequency.
Figure 2.9.: Encoder’s square wave signal, simulation of different counter clock frequency: a) 50kHz, 1MHz (±1μs), 25MHz (±40ns) ticks; b) 25MHz (±40ns), 80MHz (±12.5ns) ticks. LeCroy LC334AM
Figure 2.10.: Electric noise: a) comparison between battery and grid powered device; b) comparison between battery and grid powered device, zoom $-2 \div 10\mu s$; c) comparison between battery and grid powered device, different days; d) comparison between battery and grid powered device, day 3, different measurements.
Figure 2.11.: Speed measurement using LeCroy LC334AM: a) measurement; b) zoom $-15 \div 15\,nS$, threshold crossing; c) second rising edge, zoom $38 \div 40\,nS$; d) second rising edge, threshold crossing
Figure 2.12.: Simulation of different counting configurations
2.2. IAS Processing

The IAS acquisition used in this research is based on two hardware components:

- *the incremental encoder* with 1000 or 1024 pulses per revolution (Tekel TSW80P)
- *the counter board* National Instruments 80MHz, with Elapsed Time measurement method

The encoder generates a square wave signal as shown in Fig. 2.1 Fig. 2.3 and in the Sect. 2.1.4. The counter board output provides the measurement of the time elapsed between two rising edges as described in Sect. 2.1.1.

\[
\tau(\varphi) = \Delta t_{input} = f_{input}^{-1} = \frac{n_{count}}{f_{count}} \tag{2.13}
\]

Considering a constant angle between the encoder’s divisions, the IAS is calculated as Eq. 2.2:

\[
\bar{\omega} = n_m = \frac{2\pi f_{input}}{N} \tag{2.14}
\]

where \(N\) is the number of encoder’s divisions. The resulting speed \(\bar{\omega}\) is in fact averaged data, over an angle equal to the encoder resolution \(\Delta \varphi\). Many authors gave their IAS definitions considering nonconstant angle and other variables, [63, 12, 9, 10, 11, 13].

The measurement of one revolution \(j\) consist in an array \(P_j\) such as

\[
P_j[1 \times N] = [\bar{\omega}_1, \bar{\omega}_2, \ldots, \bar{\omega}_N] \tag{2.15}
\]

Successive \(M\) revolutions can be stored as a longer array

\[
S_{array}[1 \times (N \cdot M)] = [P_1, P_2, \ldots, P_M] \tag{2.16}
\]

or as a matrix

\[
S_{matrix}[N \times M] = [P^T_1, P^T_2, \ldots, P^T_M] \tag{2.17}
\]

The major advantage of this measurement consists in the fact that data is collected with a fixed angular reference in respect to the shaft. The signal represents the behaviour of the shaft, revolution per revolution.
2.2.1. FFT processing

An FFT processing could be applied to the IAS measurement. Filtering, aliasing and other features connected with the fft processing will be discussed in the next sections.

**Max order**  The FFT’s maximum order equals the number of encoder’s division divided by two:

\[
O_{\text{max}} = \frac{N}{2}
\]  

(2.18)

**Resolution**  The resolution of the FFT can be calculated as Eq. 2.19 and the values are reported in Table 2.3

\[
O_{\text{res}} = \frac{1}{M}
\]  

(2.19)

**Window**  Hanning, Flat top and rectangular windows’ effects are shown in the following sections.

**DC component**  The constant (DC) speed value \( \omega_0 \) appears in the spectrum as a peak at 0x order. The mean value can be removed from the whole signal applying a high-pass filter with zero phase shift set at 0.1 or 0.01 order. Another way could be to calculate the signal’s mean value of the array taken for the fft processing and subtract it from the raw signal. The latter is the better choice. In this way, only the AC signal is plotted in the spectrum.

**Scaling**  the IAS spectrum can be scaled to highlight specific orders in the plot. Normally, a linear y axis is suggested because the components have a real ratio between each other [\( \text{rad/s} \)]. Considering the power of IAS [\( \text{rad/s} \)]^2, higher components are emphasized. Squaring the IAS, [\( \text{rad/s} \)]^{1/2}, higher components (above 1) are decreased and the spectrum highlights small peaks. Choosing the decibel scale, the spectrum is normalized. Note that a specific order’s amplitude can be chosen as the reference of the dB scale.

**FFT averaging**  Spectrum averaging could be applied in order to remove the stochastic noise. After the application of an averaging process, the spectrum shows the presence of mechanical resonances in the system better.

**Filtering**  Zero-phase filtering helps preserve features in the filtered waveform exactly where those features occur in the unfiltered waveform. The MATLAB function `filtfilt` performs zero-phase digital filtering by processing the input data in both the forward and reverse directions.

<table>
<thead>
<tr>
<th>Revolutions</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>0.0078</td>
</tr>
<tr>
<td>256</td>
<td>0.0039</td>
</tr>
<tr>
<td>512</td>
<td>0.0020</td>
</tr>
<tr>
<td>1024</td>
<td>0.00098</td>
</tr>
<tr>
<td>2048</td>
<td>0.00048</td>
</tr>
<tr>
<td>4096</td>
<td>0.00024</td>
</tr>
</tbody>
</table>
**FFT’s parameter analysis - simulated signals**

Numerical signals are generated to evaluate the FFT’s parameters:

\[ \omega_{\text{sim}}(i, \alpha) = \omega_0 + \sin(i\alpha) \]  

(2.20)

and the specific cases:

\[ \omega_{\text{sim}}(\alpha) = \omega_0 + 1 \cdot \sin(4\alpha) \]  

(2.21)

\[ \omega_{\text{sim}_2}(\alpha) = \omega_0 + 1 \cdot \sin(4\alpha) + 0.25 \cdot \sin(4.008\alpha) \]  

(2.22)

\[ \omega_{\text{sim}_3}(\alpha) = 2 \cdot \sin(1\alpha) \]  

(2.23)

\[ \omega_{\text{sim}_4}(\alpha) = 0.5 \cdot \sin(0.5\alpha) \]  

(2.24)

Figure 2.13(a) and Fig. 2.13(b) show the FFT processing applied to a simulated signal obtained as Eq. 2.21. In Fig. 2.13(c) and Fig. 2.13(d) is the signal calculated as Eq. 2.22. The 4.008x order is chosen in order to simulate the presence of an electrical component owing to the slip effect. The result is very promising because the resolution can be improved to very high levels as \( \omega_{\text{res}} = 0.001 \div 0.0002 \) order, allowing the separation of the motor’s electrical components (4.008x) from the integer orders (4x).

Figure 2.14 shows the signals \( \omega_{\text{sim}_3}(\alpha) \) and \( \omega_{\text{sim}_4}(\alpha) \). In this case the test’s objective is to show how the FFT’s scaling improves the detection of specific features in the spectrum.

**FFT’s parameter analysis - real signal**

Figure 2.15 shows the effect of different windows, hanning Fig. 2.15(a), flat top Fig. 2.15(b) and rectangular Fig. 2.15(c), applied to a real signal. The Hanning window better separates the peaks while the flat top keeps the real amplitude value. Hanning window is the choice when the resolution is not high. Graphs show that at least 1024 revolutions should be considered in order to separate different signal components.

Figure 2.16 presents the effect of averaging for a resolution given by 128 and 1024 revolutions. A proper overlap value should be chosen correctly. Note in Fig. 2.16(b) the result of a 512 sample overlap with 7935 averages is better than a 128 samples overlap with 10000 averages.

Considering the filtering function, it gives the result shown in Fig. 2.17. In Fig. 2.17(a) there is one revolution of the shaft, while in Fig. 2.17(b) the same revolution is zoomed in from sample 380 to sample 480. The blue line is the original signal with 1024 pulses per revolution (ppr), while the red line is the signal obtained after the application of the `filtfilt` function. This signal has 1024 samples too. The black line is the signal downsampled to 256ppr, and the green line is this signal filtered at 128ppr.

Figure 2.18 and Fig. 2.19 show the signals after applying the FFT processing. Fig. 2.18 has a linear scale while Fig. 2.19 has a decibel scale. The results are very similar in the lower part of the spectrum, Fig. 2.18(b), while they are quite different at higher orders, especially looking at the plots in dB scale where the filter attenuation dominates the behaviour.

From an industrial point, the filter application is not considered useful because it adds a computational cost without improving the result with a significant impact. The spectral aliasing is avoided by the mechanical properties of the system.
2.2. IAS Processing

Figure 2.13.: Digital signal: a,b) order 4x, amplitude 1 rad/s, 1024 divisions; c,d) order 4x, amplitude 1 rad/s, order 4.008x amplitude 0.25 rad/s, 1024 divisions
Figure 2.14.: IAS scaling: a) simulated signal; b) linear; c) power; d) squared; e) decibel
Figure 2.15.: IAS resolution: a) hanning window; b) flat top window; c) rectangular window
Figure 2.16.: IAS averaging: a) 128 revolutions; b) 1024 revolutions
Figure 2.17.: Effect of filtering: a) 0-1024 Samples; b) 380-580 Samples
Figure 2.18.: Effect of filtering in FFT: a) 0-512 Orders; b) 27-30 Orders
Figure 2.19.: Effect of filtering in FFT: a) 0-512 Orders; b) 0-128 Orders
2.2.2. Spectral aliasing

Shannon’s sampling theorem states that a signal may be detected up to half the sampling frequency (the Nyquist frequency). This value of half the sampling frequency is equal to the maximum value of frequency seen in the spectrum without errors. Care must be taken when trying to identify and deal with errors which may arise from undersampling in the time domain and aliasing in the spectral domain. With analogue signals it is possible to use a low-pass hardware filter before the signal is sampled in order to suppress frequency components which are too high for the sampling rate used. Compared to the sampling of analogue quantities (sampling rate, sample & hold circuit), counter boards record the time interval between two rising edges of a square wave signal (Fig. 2.20), but no analog filter can be successfully applied before it is sampled, [6]. Since you cannot filter the signal, counters’ acquisition needs to be treated differently.

Rather than measuring the instantaneous angular velocity, $\omega$, at a given point on the shaft circumference, an average velocity, $\bar{\omega}$, for a finite angular interval, $\Delta \varphi$, between adjacent measurement points is measured. This causes a filtering of the measured speed amplitudes which depends on both the number of measurement points per revolution, $N$, and the rotational harmonic order of interest, $i$. The rotational speed fluctuation for a single order is Eq. 2.25

$$\omega(\varphi) = A \cos(i\varphi)$$

(2.25)

Since a cosine signal has its maximum value, $A$, at $\varphi = 0$ and assuming that the measurement points are symmetric to $\varphi = 0$ at $-\Delta \varphi / 2$ and $+\Delta \varphi / 2$, then the average rotational speed in the interval $\Delta \varphi$ is:

$$\bar{\omega}(\varphi) = \frac{1}{\Delta \varphi} \int_{-\Delta \varphi / 2}^{\Delta \varphi / 2} \omega(\varphi) d\varphi = \frac{1}{\Delta \varphi} \int_{-\Delta \varphi / 2}^{\Delta \varphi / 2} A \cos(i\varphi) d\varphi = A \frac{N}{i\pi} \sin \left( \frac{i\pi}{N} \right)$$

(2.26)

Eq. 2.26 shows that the speed measured will always be lower than $A$, its maximum value. For a given order, $i$, amplitude attenuation as a percentage is given by:

$$A(i)\% = 100 \left[ 1 - \frac{N}{i\pi} \sin \left( \frac{i\pi}{N} \right) \right]$$

(2.27)

$$\text{sinc}(x) = \frac{\sin(\pi x)}{\pi x}$$

(2.28)

The ratio $i/N = 0.5$ gives the maximum order according to sampling theory. Considering an encoder with 1024ppr and the order 512:

$$A(512)\% = 100 \left[ 1 - \frac{1024}{512\pi} \sin \left( \frac{512\pi}{1024} \right) \right] = 36\%$$

(2.29)

while for the order 100:

$$A(100)\% = 100 \left[ 1 - \frac{1024}{100\pi} \sin \left( \frac{100\pi}{1024} \right) \right] = 1.6\%$$

(2.30)

The local moving averaging process in angle can be expressed in the Fourier domain using a simple multiplication, [45. 11]:

$$\bar{\omega}(\nu) = \omega(\nu) \text{sinc}(\pi \nu \Delta \varphi)$$

(2.31)

A second intrinsic characteristic of the IAS data is that it is sampled at a sampling frequency $1/\Delta \varphi$. This angular domain sampling is equivalent to a convolution of the IAS spectrum by a comb filter with a period of $1/\Delta \varphi$. 

2.2. IAS Processing

Figure 2.20.: Angular velocity curve with angle-equidistant data points

Figure 2.21.: IAS spectral aliasing attenuation, [45]

This operation generates spectral aliasing if the IAS spectrum is not null above $1/(2\Delta \varphi)$ (the Nyquist frequency), which is not guaranteed at all by the low pass filtering expressed in Eq. 2.26, as illustrated in Fig. 2.21.

As a conclusion, the counting technique creates a low-pass filter with a cardinal sine (sinc) shape based on resolution of the encoder and the aliased phenomena are attenuated by more than 14dB in the first quarter of the spectrum. Nevertheless, it is possible to estimate the actual IAS variations of any phenomenon whose original frequency is known and subjected to aliasing in the case of low resolution encoder, [11].

Spectral aliasing is avoided by the inertia of the rotor, that works as a mechanical filter, [32]. This behaviour is confirmed by the tests conducted in our laboratory where spectral aliasing is not shown. Care must be taken when measuring an inverter fed motor. The high switching PWM components could be inside the signals (acceleration and IAS) and may be aliased.
2.2.3. Angular synchronous averaging

Angular Synchronous Averaging (ASA) is a version in angular domain of the Time Synchronous Averaging. It consists in the averaging process through various revolutions. Considering one revolution according to Eq. 2.15:

\[ P_j[1 \times N] = [\bar{\omega}_1, \bar{\omega}_2, \ldots, \bar{\omega}_N] \]  

(2.32)

The averaged signal simply consists in:

\[ A[N \times 1] = \frac{1}{M} \sum_{j=1}^{M} P_j^T \]  

(2.33)

and it represents the shaft mean speed during multiple revolutions. The same value could be calculated with the matrix approach (Sect. 2.3). Then, the signal is reconstructed copying the array \( A \) for \( M \) times, exactly the same number of revolutions of the original signal.

\[ A_M[1 \times N \times M] = [A^T, A^T, \ldots, A^T, \ldots, A^T] \]  

(2.34)

Now the FFT processing is applied. The resulting spectrum contains only integer orders, as a comb filter Fig. 2.22(a) This can be subtracted from the original spectrum, removing all the integer components, Fig. 2.22(b) This is very useful when considering a system with non integer components such as bearings, or, as in the case of electric induction motors, electrical orders due to slip and other electromagnetic effects. ASA could be adopted as a correction of encoder’s geometrical error, [65]. But note that Fig. 2.22(a) shows different amplitudes. Increasing the number of averages, the output changes quite a lot, also due to the slip presence. This amplitude error produces the negative values in the spectrum of Fig. 2.22(b).

2.2.4. Encoder correction

In this section a method to correct the encoder’s geometrical error is proposed. Basically, the idea is to calculate the exact encoder’s segment length through an optimization algorithm. The objective of the process is to minimize integer orders. A population of elements calculated as:

\[ \phi_{\text{enc}}[1 \times N] = [\Delta \varphi_1, \Delta \varphi_2, \ldots, \Delta \varphi_i, \ldots, \Delta \varphi_N] \]  

(2.35)

Considering a random error:

\[ E_{\text{enc}}[1 \times N] = (e_g/100) \cdot \text{rand}(−1 ÷ 1) \cdot \phi_{\text{enc}} \quad e_g = 0.01 \]  

(2.36)

\( E_{\text{enc}} \) is used to calculate the IAS, \( \bar{\omega} \), so optimization parameters are:

- input variable: \( E_{\text{enc}} \)
- output variable: IAS spectrum
- objective: minimization of IAS spectrum’s integer orders

The optimization calculates only the Design Of Experiments (DOE) without applying a specific algorithm (eg. simplex) because the result agrees with the expectations. Further research can be done in this field in order to render the optimization process faster. Fig. 2.23 and Fig. 2.24 shows the effect of this process with real measurement data. Note that using the encoder’s correction algorithm, the negative values due to ASA are not present.

After the encoder’s calibration, the system is ready to start the monitoring of a machine and an increase of a specific integer order will be seen in the spectrum.
Figure 2.22.: Angular Synchronous Averaging: a) ASA spectrum; b) IAS spectrum without ASA spectrum
Figure 2.23.: Encoder correction

Figure 2.24.: Encoder correction vs Angular Synchronous Averaging
2.3. Matrix Approach

2.3.1. Data storage and analysis

In order to manage and analyze IAS data, it is better to organize the acquisitions in matrix instead of array. In this way, data processing in MATLAB is faster than searching the element of the array (e.g. time spent calculating the maximum value: 0.009472 seconds for a matrix [1024, 4000], versus 0.095316 seconds for an array [1024 * 4000]). In our data processing, each element $p_{ij}$ of the matrix $S$ represents the instantaneous angular speed of a single division of the encoder Eq. 2.39 A row array $R_i$ represents multiple turns of the shaft Eq. 2.38 A column array $P_j$ contains all the encoder divisions Eq. 2.37, so it represents a single revolution.

$$P_j[n \times 1] = [p_{1j} \ldots p_{ij} \ldots p_{nj}]^T$$  

(2.37)

$$R_i[1 \times r] = [p_{i1} \ldots p_{ij} \ldots p_{ir}]$$  

(2.38)

$$S[n \times r] = [P_1 \ldots P_j \ldots P_r]$$  

(2.39)

$$S[n \times r] = \begin{bmatrix}
  p_{11} & \ldots & p_{1j} & \ldots & p_{1r} \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  p_{i1} & \ldots & p_{ij} & \ldots & p_{ir} \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  p_{n1} & \ldots & p_{nj} & \ldots & p_{nr}
\end{bmatrix}$$  

(2.40)

$$S[1024 \times 4] = \begin{bmatrix}
  p_{1,1} & p_{1,2} & p_{1,3} & p_{1,4} \\
  p_{2,1} & p_{2,2} & p_{2,3} & p_{2,4} \\
  \vdots & \vdots & \vdots & \vdots \\
  p_{1024,1} & p_{1024,2} & p_{1024,3} & p_{1024,4}
\end{bmatrix}$$  

(2.41)

$n$ is the number of encoder divisions, while $r$ is the number of revolutions. An example is reported in Eq. 2.41: encoder with 1024 divisions and 4 revolutions. Now it is possible to simply and quickly analyze data along rows and columns.

Removing encoder geometry error. It is possible to remove the encoder’s non uniform spacing error calculating the mean value along rows, so removing the mean value of many revolutions of a single encoder’s sector. This comes down to the Angular Synchronous Averaging [65]: every integer order is removed from the signal. This could be useful for isolating non integer orders: bearing signals and load variations. Using a high quality encoder, it is not necessary to use the Angular Synchronous Averaging.

Removing the mean value of the speed by calculating the mean value along columns, the mean value of the single turn is obtained. Sometimes it is useful to remove it for further signal processing: e.g., the load variation can be evaluated over the signal shape changes.

Statistical analysis Using matrix instead of arrays is quite useful in order to simplify the MATLAB signal processing: For example, it is possible to quickly draw a 3D map of the signal or calculate a statistical parameter along turns or encoder’s divisions. In the next section, maximum, rms, peak and kurtosis values are calculated and analyzed.
2.3.2. Statistical results

Organizing data into matrix (divisions vs revolutions) allows to calculate the statistical parameters along two directions: rows or columns. Fig. 2.25 In this example, a group of 128 divisions per 800 revolutions is selected. First, the calculation direction should be chosen and an array is generated with the result. Selecting the row direction, a column vector is obtained with the length equal to the number of the encoder’s divisions. The array size can be further reduced calculating another statistical parameter: e.g. mean, mode or median of the array. In Fig. 2.26 2.30 the mean value is chosen. The experimental test rig (Sect. 4.3) is tested in four different conditions:

- no fault - no load
- no fault - with load
- with fault - no load
- with fault - with load

During the test, 4000 revolutions of the shaft have been acquired (Fig. 2.26 2.30). The signal is filtered in order to remove the quantization error. The presence of a fault in the inner ring creates a non constant speed fluctuation in time, Fig. 2.26(b) 2.27(c) 2.27(d) Fig. 2.28 reports the evolution of maximum and minimum values with revolutions (red lines): only three revolutions are selected in order to show the motor’s slip effect. Comparing the figures on the left (Fig. 2.28(a) 2.28(c)), no fluctuation occurs, while figures on the right (Fig. 2.28(b) 2.28(d)) shows the fluctuation that generates the maximum peak value. This phenomenon could be related to a specific position of the ball along the revolution. Figures 2.29 2.30 report the kurtosis and peak values calculated along rows and columns.

**Maximum value** The maximum row value has a mean value quite constant with revolutions (Fig. 2.26 Fig. 2.27), and could be useful for fault alarm.

**Rms value** The rms values have the same mean values along rows and columns. Nevertheless this parameter does not allow a good separation between test conditions.

**Peak value** The peak value is calculated from the maximum minus the minimum values of the signal (Fig. 2.30). In this case, the graphs present a different information: peak row mean does not seem useful; peak col mean and peak row max can separate the tests in the exact load sequence (min to max load); peak col max has the better separation between faulty and no faulty conditions.

**Kurtosis value** Only the mean value of the kurtosis calculated along columns seems to have the signal separation property (Fig. 2.30).

As a conclusion, the IAS is capable of also providing information outside the measured machine. This is quite a remarkable result considering the total inertia of the rotating part of the setup and the speed variation deriving from a damage on a bearing. It obviously relies on very high count encoders and high frequency counters, but allows to characterize the machine in a fast and powerful way. The proposed approach is promising as the results demonstrate. Further statistical tools and processing techniques are under investigation to increase the diagnostic capabilities of IAS that will be the subject of future papers.
Figure 2.25.: Matrix size reduction for statistical analysis: e.g. selection of a group of 128 encoder divisions and 800 shaft revolutions

Figure 2.26.: 3D matrix plot, 4000 revolutions, 8x10 sub-group, maximum value: a) with load - no fault; b) with load - with fault
Figure 2.27.: 2D matrix plot, 4000 revolutions, 8x10 sub-group, maximum value: a) no load - no fault; b) with load - no fault; c) no load - with fault; d) with load - with fault

Figure 2.28.: 2D matrix plot, 4000 revolutions, 8x10 sub-group, maximum value: a) no load - no fault; b) with load - no fault; c) no load - with fault; d) with load - with fault
2.3. Matrix Approach

Figure 2.29.: Kurtosis IAS value in no load conditions, with and without fault, 128x500 sub-groups: a) row direction; b) column direction

Figure 2.30.: Peak IAS value in no load conditions, with and without fault, column direction, 8x10 sub-groups: a) top matrix view; b) side view, evolution
3. Measurement’s Source of Errors

IAS measurement errors come from different sources. Generally speaking, the absolute error value, increases linearly with the speed and the resolution of the encoder, considering that the upper measured speed limit is the ratio between the encoder’s resolution and the clock frequency of the counter. The ideal encoder assumes exactly equal geometric segments and any variation causes the ET to be sampled on a non-uniform angular basis. Since the spacing pattern repeats itself after each revolution, the error manifests itself as high-level content at integer multiples of the shaft running speed. It is possible to use the synchronous averaged encoder passage times to correct for the uneven encoder spacing [65]. These errors are unavoidable, but the production standards are very high and great precision can be obtained. The ET measurement depends on the achievable time resolution, governed by the clock rate and the zero crossing detection circuit. These lead to two main problems: the counting method and the clock stability. Different authors [91, 9] have analysed the problems and have suggested appropriate remedies. Further errors can be experienced if the sensor undergoes lateral movement, if the shaft’s eccentricity mounting misalignment or if any light-path transmission variations are present.

3.1. IAS’ Error Sources

3.1.1. Encoder’s geometrical error

In order to understand how the encoder’s geometry influences the IAS spectrum, a random error is applied to one revolution:

$$\Delta \varphi = \frac{2\pi}{N}$$  \hspace{1cm} (3.1)

$$\phi_{enc}[1 \times N] = [\Delta \varphi_1, \Delta \varphi_2, \ldots, \Delta \varphi_i, \ldots, \Delta \varphi_N]$$  \hspace{1cm} (3.2)

$$\sum_{i=1}^{N} \Delta \varphi_i = 2\pi$$  \hspace{1cm} (3.3)

Calculating Eq. 2.2 and Eq. 2.15.

$$P_{th_j}[1 \times N] = [\bar{\omega}_{th_1}, \bar{\omega}_{th_2}, \ldots, \bar{\omega}_{th_i}, \ldots, \bar{\omega}_{th_N}]$$  \hspace{1cm} (3.4)

with

$$\bar{\omega}_{th_i} = f_{input} \Delta \varphi_i$$  \hspace{1cm} (3.5)

Considering a random error:

$$E_{enc}[1 \times N] = (e_g/100) \cdot rand(-1 \div 1) \cdot \phi_{enc} \quad e_g = 1, 0.1, 0.01$$  \hspace{1cm} (3.6)

with

$$\sum_{i=1}^{N} E_{enc_i} = 2\pi$$  \hspace{1cm} (3.7)
the IAS is calculated, obtaining:

\[ P_{er} [1 \times N] = [\bar{\omega}_{er_1}, \bar{\omega}_{er_2}, \ldots, \bar{\omega}_{er_i}, \ldots, \bar{\omega}_{er_N}] \]  

\[ \bar{\omega}_{er_i} = f_{input_i} E_{enc_i} \]  

The FFT processing is applied. Fig. 3.1 shows a real measurement of an asynchronous motor running at 1500rpm with simulated errors. Figure 3.1(c) presents a spectrum similar to the one without the simulated error, so the encoder’s geometrical error may be less than 0.01%.

This approach does not take into account the fact that the time is counted with the angular reference and so a geometrical error affects the parameter \( f_{input_i} \). In order to calculate the real IAS \( \bar{\omega}_{rea_i} \), the real angle \( \Delta \varphi_{rea_i} \) should be known.

\[ \bar{\omega}_{rea_i} = f_{input_i} \Delta \varphi_{rea_i} \]  

Note that Eq. 3.10 does not consider the quantization error, Sect. 3.1.2. Many authors approached this problem [65, 45, 91, 9], especially when a zebra tape or a phonic wheel is used (where the geometrical error is bigger). [65] says that an incremental optical encoder has a sufficient quality for industrial applications. [45] tried to measure the encoder’s real angle using a lathe in order to keep the speed as much constant as possible, avoiding speed fluctuations. A system able to measure the encoder’s error would be very interesting for industrial applications.

**Signal processing**  Basically two solutions has been tested during the PhD research in order to remove encoder geometrical errors:

- Angular Synchronous Averaging (array and matrix approaches, Sect. 2.2.3 and Sect. 2.3 )
- Encoder correction (estimation of encoder geometry through a random research, Sect. 2.2.4)

### 3.1.2. Counter’s quantization error

Generally speaking, the absolute error value, increases linearly with the speed and the resolution of the encoder, considering that the upper measured speed limit is the ratio between the encoder’s resolution and the clock frequency of the counter. The ET method: the rising edge of the input signal of the encoder triggers the counting of the timebase ticks. Since the timebase is of a known frequency, the frequency of the input signal can be obtained as Eq. 2.13.

Many authors studied the effect of the uneven encoder spacing [65, 45], the counting method effect and the clock stability [9, 63]. Further errors can be experienced if the sensor undergoes lateral movement, if it is installed with eccentricity or misalignment, or if any light-path transmission variations are present. The most important error is the quantization error and it is calculated as Eq. 3.11:

\[ \pm \Delta \omega = \frac{\omega^2}{1 \pm \frac{2\pi f_{count}}{N}} \]  

(3.11)

It is related to the shaft speed, the counter clock frequency and the number of encoder’s divisions. Table 3.1 shows its variation. An experimental test rig was developed in order to avoid this kind of errors and enhancing the test quality.
Figure 3.1.: Geometrical Error, induction motor running at 1500rpm
Table 3.1.: Quantization error estimation: bold font represents the same configuration; in red color, two configurations with the same percentage error at different shaft speed and clock freq

<table>
<thead>
<tr>
<th>Counter Frequency $f_{count}$ [MHz]</th>
<th>Motor Speed $\omega$ [rad/s]</th>
<th>Encoder divisions $N$</th>
<th>Quantization Error $\pm \Delta \omega$</th>
<th>$\pm %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>157 (1500 rpm)</td>
<td>1024</td>
<td>4.0165</td>
<td>2.5583</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>0.2009</td>
<td>0.1279</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td>0.0502</td>
<td>0.0320</td>
</tr>
<tr>
<td>800</td>
<td></td>
<td></td>
<td>0.0050</td>
<td>0.0032</td>
</tr>
<tr>
<td>8000</td>
<td></td>
<td></td>
<td>0.0005</td>
<td>0.0003</td>
</tr>
<tr>
<td>80</td>
<td>15.7 (150 rpm)</td>
<td>1024</td>
<td>0.0005</td>
<td>0.0032</td>
</tr>
<tr>
<td>78.5 (750 rpm)</td>
<td></td>
<td></td>
<td>0.0126</td>
<td>0.0160</td>
</tr>
<tr>
<td>157 (1500 rpm)</td>
<td></td>
<td></td>
<td>0.0502</td>
<td>0.0320</td>
</tr>
<tr>
<td>314 (3000 rpm)</td>
<td></td>
<td></td>
<td>0.2009</td>
<td>0.0640</td>
</tr>
<tr>
<td>80</td>
<td>157 (1500 rpm)</td>
<td>256</td>
<td>0.0126</td>
<td>0.0080</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.0251</td>
<td>0.0160</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.0502</td>
<td>0.0320</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1004</td>
<td>0.0640</td>
</tr>
</tbody>
</table>

Figure 3.2(a) 3.2(b) show the IAS measurements of the motor running at about 1500rpm. The counter at 20MHz clearly shows the quantization error ($\pm 0.2009$ rad/s, $\pm 0.1279\%$), while the 80MHz counter presents a better result ($\pm 0.0502$ rad/s, $\pm 0.0320\%$). Fig. 3.2(c) has a small quantization error ($\pm 0.0005$ rad/s, $\pm 0.0032\%$) because the motor is running at 150rpm. An 800MHz counter should be used in order to get the same percentage error at 1500rpm (Table 3.1) and an unfeasible 8GHz counter for the same absolute value. That said, it is mandatory to use the highest counter speed available for statistical analysis.

Figure 3.3 shows the quantization effect in the IAS spectrum. The noise is present at high orders, but in the lower part of the spectrum, the two measurements are almost the same. From an industrial point of view they could be considered identical.

### 3.1.3. Experimental test

In order to separate the geometrical error from the quantization error, an experiment is done using:

- Signal generator
- Oscilloscope LeCroy LC334AM (500Ms/s)
- Counter Board (National Instruments 80MHz)

A square wave is generated with the signal generator set at 25kHz in order to simulate an electrical induction motor with 4 poles powered by 50Hz three phase supply current running at 1500rpm with a certain slip, with a resulting mean frequency of 24642.54 Hz, that equals the mean speed of 24.64 Hz (1478.55 rpm). Four periods are acquired with the oscilloscope and the resulting frequencies are:

<table>
<thead>
<tr>
<th>Signal 1</th>
<th>Signal 2</th>
<th>Signal 3</th>
<th>Signal 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>24696.14</td>
<td>24695.03</td>
<td>24695.45</td>
<td>24695.08</td>
</tr>
<tr>
<td>1481.77</td>
<td>1481.70</td>
<td>1481.73</td>
<td>1481.70</td>
</tr>
</tbody>
</table>

Table 3.2.: Frequency calculated from the rising edges of the square wave
Figure 3.2.: Counter clock frequency comparison: a) 20MHz counter, with and without load; b) 80MHz counter, with and without load; c-d) 80MHz counter, motor running at 150rpm without load - low quantization error
Figure 3.3.: Quantization error in IAS spectrum, counter 80MHz vs 20MHz without load: a) 0-50x; b) 250-500x
with:

\[ \text{rpm} = \frac{60 \cdot \text{frequency}}{1000} \]  

(3.12)

the mean is calculated as:

\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  

(3.13)

while the standard deviation as (for a small \(n\)):

\[ \sigma_1 = \left[ \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{\frac{1}{2}} \]  

(3.14)

or as the second moment of the set of values about their mean:

\[ \sigma_2 = \left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{\frac{1}{2}} \]  

(3.15)

and the relative standard deviation:

\[ \sigma^* = \frac{\sigma}{|x|} \]  

(3.16)

<table>
<thead>
<tr>
<th>( \bar{x} )</th>
<th>( \sigma_1 )</th>
<th>( \sigma_2 )</th>
<th>( \sigma^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24695.42</td>
<td>0.51</td>
<td>0.45</td>
<td>0.000018 [Hz]</td>
</tr>
<tr>
<td>1481.725</td>
<td>0.031</td>
<td>0.027</td>
<td>0.000018 [rpm]</td>
</tr>
</tbody>
</table>

Table 3.3.: Statistical values

<table>
<thead>
<tr>
<th>( \text{min} )</th>
<th>( \text{mean} )</th>
<th>( \text{median} )</th>
<th>( \text{max} )</th>
<th>( \sigma_2 )</th>
<th>( \sigma^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24638.13</td>
<td>24642.54</td>
<td>24645.72</td>
<td>24653.31</td>
<td>3.75</td>
<td>0.00015 [Hz]</td>
</tr>
<tr>
<td>1478.29</td>
<td>1478.55</td>
<td>1478.74</td>
<td>1479.20</td>
<td>0.25</td>
<td>0.00015 [rpm]</td>
</tr>
</tbody>
</table>

Table 3.4.: Statistical values with counter board

In Table 3.4 are reported the statistical values calculated with the counter board. The standard deviation has a scale factor of 10 between the two measurements. The difference between the maximum and the median value of the signal is:

\[ \frac{1}{24645.72} - \frac{1}{24638.13} = 7.59 \text{Hz} \]

\[ \frac{1}{24645.72} - \frac{1}{24638.13} \simeq -1.25 \cdot 10^{-8} s = -12.5 ns \]

\[ \frac{1}{80 MHz} = 12.5 \cdot 10^{-9} s \]

This is due to the presence of the quantization error. There is also a difference between the measurements’ mean values, Fig. 3.4:

\[ 24695.42 - 24642.54 = 52.89 \text{Hz} \]

This error could be related to the different behaviour of the two electronic systems.
Figure 3.4.: Square wave: a) 24695.4233 Hz, LeCroy LC334AM, trigger 2.08V; b) 24642.537 Hz, NI counter

The FFT processing is applied at the signal acquired with the counter board, Fig. 3.5. The figure does not show the DC component of the signal, that is the simulated mean speed. Electric components are present at 50Hz and 130Hz and their harmonics. There is no 1x order.

\[
2.028 \times \frac{24645.72}{1000} = 49.98 \text{Hz} \approx 50\text{Hz}
\]

\[
5.262 \times \frac{24645.72}{1000} = 129.69 \text{Hz} \approx 130\text{Hz}
\]

A random noise is present at high orders. This could be attributed to the spectral aliasing because in this case there is no mechanical filter that avoids the presence of higher order components.
Figure 3.5.: Square wave at 24642.537 Hz, simulated encoder with 1000ppr: a) range 0-500x, electrical noise; b) range 0-30x, order 2.028 - 50Hz, order 5.262 - 130Hz power line
3.2. Other Error Sources

3.2.1. Clock stability

The accuracy specification of a clock describes how much deviation there can be between the specified clock frequency and the actual frequency. The stability specification gives a measure of how much the frequency varies over time.

**Accuracy**  If a clock has a counting frequency of 20 MHz and the accuracy is 0.01%, the absolute minimum and maximum frequency can be calculated as follows:

\[
\text{Maximum Frequency} = 20,000,000 + (20,000,000 \times 0.0001) = 20,002,000Hz \quad (3.17)
\]

\[
\text{Minimum Frequency} = 20,000,000 - (20,000,000 \times 0.0001) = 19,998,000Hz \quad (3.18)
\]

Anytime the clock runs, its frequency is somewhere in the range between the minimum and the maximum.

**Stability**  The stability of the clock is typically specified in percent per unit time (for example, 0.0001%/year) or parts per million per unit time (for example, 100ppm/year).

In other words, the time between two occurrences separated 100 times is measured, if the clock is drifting between the minimum and maximum, it is not stable over time and the two separate measurements cannot be compared. If the clock does not drift at all, it is stable over time and the two measurements can be compared. The frequency measurement or generation accuracy, sometimes called timing accuracy, is usually given in ppm (parts per million) of the sample rate and can be found in many specifications manuals for the device in question. The common equation is:

\[
\text{Measured frequency} (f_m) = \text{signal frequency} (f_s) \pm \text{frequency error} (f_e)
\]

\[
\text{Frequency error} (f_e) = \text{signal frequency} (f_s) \times \text{frequency accuracy} (f_a)
\]

**Examples 1:**  Consider a case where a true 100kHz sine wave should be measured using a device with a frequency accuracy of 25 ppm. The frequency error will be around 100,000Hz \times 25/1,000,000 = 2.5Hz. Therefore, the measured frequency accuracy is 100kHz ± 2.5Hz.

Consider a case in where a 1kHz sine wave should be measured using a device with a frequency accuracy of 50 ppm. The frequency error will be around 1,000Hz \times 50/1,000,000 = 50mHz. Therefore, the measured frequency accuracy is 1kHz ± 50mHz.

**Examples 2:**  Units used for stability are typically parts per million (ppm) and parts per billion (ppb). For example, the frequency of a 10 MHz oscillator with 10 ppm stability can be 10 MHz ± 100 Hz; with 100 ppb stability it can be 10 MHz ± 1 Hz. The best technique for improving oscillator stability is to precisely control its temperature as is done in an oven-controlled crystal oscillator (OCXO) obtaining 75ppb.

<table>
<thead>
<tr>
<th>Clock Stability</th>
<th>Counter Frequency</th>
<th>Error</th>
<th>12.5ns</th>
<th>1/80000000</th>
</tr>
</thead>
<tbody>
<tr>
<td>50ppm</td>
<td>80MHz</td>
<td>±4000Hz</td>
<td>-6.25 \times 10^{-13} = 1/8004000 - 12.5 \times 10^{-9}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.25 \times 10^{-13} = 1/79996000 - 12.5 \times 10^{-9}</td>
<td></td>
</tr>
<tr>
<td>75ppb</td>
<td>80MHz</td>
<td>±6Hz</td>
<td>-9.375 \times 10^{-16} = 1/80000006 - 12.5 \times 10^{-9}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.375 \times 10^{-16} = 1/79999994 - 12.5 \times 10^{-9}</td>
<td></td>
</tr>
</tbody>
</table>
3.2.2. Electrical noise

Encoders and other different sensors (inductive, capacitive, laser) can be affected by electromagnetic noise and other errors, like missing teeth in a flywheel and unequal spacing in zebra tape. Fig. 3.6 shows some examples of noise and correction algorithms. For example, an algorithm could estimate the passing time between two teeth and if other peaks are found, it skips the measurement. The same approach could be adopted when there are missing teeth. This is noticed in A/D measurements, in counter board devices the electronic hardware must take into account this kind of error and automatically adjust the result.

Figure 3.6.: Tacho processing: a) tacho signal; b) tacho signal, zoom 16, 5 ÷ 18s; c) tacho processing; d) tacho processing, zoom; e) signal correction; f) signal correction, zoom
4. Experimental Tests

The experimental setups are described in the following paragraphs:

- The first experimental test rig, called ETR1, is used for the comparison between the Instantaneous Angular Speed measured with the encoder (also with different counting methods) and with the Torsional Laser Vibrometer, [77]. Another comparison is done between the IAS and the acceleration, [75]. The measurements are taken with varying (inverter) and fixed (50Hz power supply) speed, but without load.

- The second experimental test setup, ETR2, is used for a measurement with different loads applied. In this case, a hysteresis magnetic brake is attached to the motor. The Magneto Motive Force (MMF) effect is studied, [78].

- A third experimental test rig, ETR3, is designed and built in order to simulate a BPFI bearing fault in the system. A synchronous generator is coupled to the motor in order to generate a variable load. A matrix based statistical method is proposed in Sect. 2.3 using this setup, [76].

- Two measurements are also taken at the company, but considering brand new motors only (CR 900 X4 and CT 560 Y4). It was not possible to take measurement on a faulty one. The setups are presented in Sect. 4.4.

The data acquisition system is based on National Instruments hardware, using the internal tunable counter and purposely developed software. Analog signals are collected at 51.2kHz, while the encoder’s signal uses a 20-80MHz counter. The purposely developed MATLAB software, called JaSaT - Instantaneous Angular Speed Analysis Tool, does the necessary signal processing. A description is reported in Appendix D.

4.1. Experimental Test Rig - 1

The first test setup consists of a 1kW 4 poles electric induction motor. The motor is coupled with an optical encoder with a resolution of 1000ppr. The motor and the encoder’s support are fixed to a stiff base plate in order to avoid relative motions between them. The encoder’s shaft is rigidly connected to the rotor, while its body is kept in position through a spring fixed to the baseplate. The motor is powered by a TOSHIBA inverter VFS-11 or by 50Hz 380V current line. In Fig. 4.1, there also is a tri-axial accelerometer PCB 356A16 (the X axis in tangential, the Y in the axial and the Z in the radial direction) and a photoelectric tachometer probe (B&K MM0024). The B&K Torsional Vibration Meter (TVM) Type 2523, also called Torsional Laser Vibrometer (TLV) in this thesis, is sustained by a tripod and it is not affected by the motor vibrations. The B&K hardware settings are: range 1000Hz, hi-pass filter 0.3Hz, low-pass filter 1000Hz. The TVM lasers are focused on the outer rim of a pulley covered with retro-reflective tape to assure good and uniform beam reflections. The characteristic frequencies of the installed motor bearing (type 6204-2RS1) are listed in Table 4.1.
Table 4.1.: Characteristic orders, bearing 6204-2RS1

<table>
<thead>
<tr>
<th>Defect</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass Pass Frequency - Inner</td>
<td>BPFI</td>
</tr>
<tr>
<td>Bass Pass Frequency - Outer</td>
<td>BPFO</td>
</tr>
<tr>
<td>Fundamental Train Frequency (Cage)</td>
<td>FTF</td>
</tr>
<tr>
<td>Ball Spin Frequency (Rolling element)</td>
<td>BSF</td>
</tr>
</tbody>
</table>

Figure 4.1.: Experimental set-up: Torsional Laser Vibrometer, Encoder, Accelerometer

Figure 4.2.: TVM position test setup
4.1.1. Motor behaviour

Due to the motor type, the slip effect is present. It is possible to view this phenomenon in Fig. 4.3 where signals from an AC and a DC motor are compared. The main component of the signal is the electromagnetic force seen by the rotor and its frequency is given by Eq. 4.6 where \( p \) is the number of pole pairs, \( n_m \) is the mechanical speed, \( f \) is the fundamental supply frequency and \( n_s \) is the synchronous speed. In time/angular domain, it appears as a shifting waveform due to the fact that there is a difference between the mechanical rotating speed and the magnetic field in the stator. This effect doesn’t appear with synchronous or DC machines because mechanical and electrical speeds are synchronized.

\[
f = \frac{p}{1 - s} n_m
\]

\[o_e = \frac{p}{1 - s}\]  

\[n_s = \frac{f}{p} = \frac{50Hz}{2} = 25Hz\]  

\[s = \frac{n_s - n_m}{n_s} = \frac{25 - 24.95}{25} = 0.002\]

Considering the motor running at about 1497 rpm, the slip Eq. 4.4 is \( s = 0.002 \).

The Magneto Motive Force (MMF), accurately studied in the Sect. 4.2.2, generates the peaks at the orders:

\[o_e = \frac{p}{1 - s} = \frac{2}{1 - 0.002} = 2.004\]

\[2o_e = 2 \cdot 2.004 = 4.008\]

\[4o_e = 4 \cdot 2.004 = 8.016\]

\[6o_e = 8 \cdot 2.004 = 12.024\]

Fig. 4.4 presents four plots zooming around orders 2, 4 and 8. The orders generated by the MMF space harmonics are shown. The 4.008 order has the highest amplitude. There are sidebands at pole pass \( pps = 0.008 \) around each peak owing to the slip and the pole pairs:

\[pps = 2p \cdot s = 2 \cdot 2 \cdot 0.002 = 0.008\]

another notation could be used:

\[pps = \frac{2sf}{n_m} = 2ps\frac{n_s}{n_m} = \frac{2ps}{1 - s} \frac{n_m}{n_m} = \frac{2ps}{1 - s} = 2o_e \cdot s = 2 \cdot 2.004 \cdot 0.002 \simeq 0.008\]

where \( sf \) is called slip frequency. In order to define the right formula for the sideband’s calculation, the experimental test rig 2 (ETR2) is tested under different loads.

Experimental Test Rig - 1 is used to show the motor behaviour at different speeds (Fig. 4.5) and different counting methods (Fig. 4.6). The motor is tested at: 150, 300, 500, 700, 1000 and 1500 rpm; using a Toshiba VFS11 inverter. Note the different signal shape. The amplitude of AC component decreases with the increase in speed, probably due to the combination of the motor and the inverter behaviours.

The ET and LR methods described in the Sect. 2.1.1 are compared: the ET (one counter method) with 1000ppr; the LR method using two counters, with a divisor set at values: 5, 10, 20 giving respectively 200, 100, 50 pulses/revolution (ppr). The LR simply decimates the signal.
Figure 4.3.: Three cycles at $0 - 360^\circ$ and zoom at $180 - 270^\circ$: a) AC motor, 150rpm, encoder 1000ppr, with slip effect; b) DC motor, 515rpm, encoder 120ppr, without slip effect

Figure 4.4.: IAS: slip order 2.004 and its harmonics 4.008, and 8.016
Figure 4.5.: IAS raw signal at 150rpm, 300rpm, 500rpm, 700rpm, 1000rpm, 1500rpm
Figure 4.6: IAS encoder, different estimation method and speed, [a,c,e] 1000ppr ET; b,d,f) 200ppr LR: a-b) 300rpm; c-d) 500rpm; e-f) 700rpm
4.1.2. Torsional Laser Vibrometer

Two different approaches to obtain the IAS estimation will be compared: an encoder-counter system versus a torsional vibrometer. The systems rely on two totally different approaches and ways of working: one being with contact and one without. In [77] is reported the complete test. The results are summarized in the following paragraphs.

The B&K Torsional Vibration Meter (TVM) Type 2523 processes the interferometric signal deriving from the combination of two laser beams impinging on the rotating shaft. The light, coming from a single low-powered (2mW) laser source, is backscattered and collected by a photodetector. The current output of the photodetector is modulated by the difference in frequency between the two beams. Whirling, axial vibrations and torsional vibrations may be detected [39, 38]. The frequency difference can be written as Eq. 4.11 [50].

\[
f_d = \left( \frac{4\mu \pi d}{\lambda} \right) N \cos \beta \sin \alpha
\]

(4.11)

where \( \mu \) is refractive index (\( \mu = 1 \) in air), \( N \) is the rotation speed in Hertz, \( \lambda \) is the laser wavelength (780nm), and \( d \) is the perpendicular beam separation, \( \alpha \) and \( \beta \) are the instrument installation angles. The torsional vibration will be seen as fluctuations in \( N \). The system does not require special calibrations, but the use of a retro-reflective tape is mandatory for high quality measurements. The positioning of the instrument is very important for the accuracy of the measurement. The TVM is sensitive to the target’s lateral vibration, which contributes to the angular measurement and it is indistinguishable from the torsional vibration. It should be noted that such angular lateral vibration includes not only the shaft bending vibration but also the solid body motions such as an engine block rocking in its mounts. If such solid body motions are of concern, accelerometer measurements should be made for comparisons with the data taken directly from the rotating shaft.

**Measurement noise: dropouts and laser speckle**

A speckle pattern is formed when the light coming from a coherent light source (laser beam) shines onto an optically rough surface (roughness comparable with the light wavelength). It consists of a distribution of light and dark spots, that changes with the surface motion and thus the Doppler modulation. Considering a rotating target, the random speckle pattern is repeated once per revolution (whenever the same population of scatterers is illuminated), resulting in the noise having a pseudo-random nature. This leads to relatively equal amplitude peaks in the frequency spectrum at the first rotor order up to the high order harmonics, Fig. 4.11 and is indistinguishable from genuine vibration information, [69].

Another problem is the dropout that can occur when the Doppler signal amplitude drops so low that the vibrometer cannot accurately demodulate it and the apparent velocity cannot adequately be resolved. Fig. 4.7 shows a signal from a tilting surface, with the laser beam aligned off the rotational axis of the surface, exhibiting broadband speckle noise (Fig. 4.8) and also significant periodic dropouts. These impulses contain significant energy and can raise the broadband noise to levels where a useful measurement becomes compromised.

**TVM position effect**

A test is conducted to evaluate the influence of laser measurement position on speckle noise. A nylon pulley is added to the system, increasing the diameters to 80mm and 135mm (Fig. 4.2). The position of the laser was set at 200mm and 400mm, between the recommended distance values (5-500mm). The motor is driven from 150rpm to 1500rpm in order to evaluate the difference with different speeds. The range of B&K 2523 is set at 100Hz, evaluating the four Low Pass (LP) filters (1000Hz, 300Hz, 100Hz, 30Hz). Fig. 4.9 depicts the system
using a 1000Hz LP filter at 150rpm. There is no difference between the signals of the two pulley diameters (Fig. 4.9(a) 4.9(b)). Instead, the measurement results are noisier at 400mm (Fig. 4.9(c) 4.9(d)). The results obtained in this PhD research confirms what was explored by [49], setting an optimal measurement distance of 200mm for B&K 2523. The distance correlation could be a problem in periodic condition monitoring because the position of the instrument changes at every check.

**Raw signal evaluation**

In order to compare the signal from the TVM output and that of the encoder, it is necessary to filter the latter’s speed signal, obtaining its AC component.

In Fig. 4.10 the measurements are reported in rad/s. The motor is tested every 50rpm, from 150rpm to 1500rpm. The measurements on the left are a raw signal. The TVM shows a speckle noise problem because the internal speckle noise suppression is turned off during the acquisition of the measurements in order to evaluate the effective behaviour of the system without a signal manipulation. Instead, the signals on the right are obtained applying a low-pass filter.

**FFT evaluation**

In order to compare the velocity estimates from the TVM and the encoder, a FFT processing is applied. To visualize the results, the angle domain is chosen. The encoder signal is already in the proper domain, instead the TVM output needs an angular resampling. The comparison (Fig. 4.11) shows the ET 1000ppr encoder signal and TVM resampled at 1000ppr. The TVM signal presents noise due to a speckle pattern: the difference in amplitude between the two spectrums demonstrates that the speckle noise has a bigger impact on the IAS measurement than the encoder’s geometrical error. At low orders the effect is high while over the order 100 the signal is filtered by the B&K hardware. The encoder signal presents the opposite behaviour: at low order the signal is good while at higher order there is a quantization error.

**Angular Synchronous Averaging**

Fig. 4.12 shows the FFT processing without synchronous components due to an Angular Synchronous Averaging (ASA) processing. ASA removes the components related to speckle noise and encoder’s imperfections. The results for the main components is the same, showing the predominant order 4.008 and its harmonics.
Figure 4.8.: Example of laser pattern [48]

Figure 4.9.: TVM output range 100, 1 cycles at 150rpm, LP filter 1000Hz: a) distance 200mm - diameter 80mm; b) distance 200mm - diameter 135mm; c) distance 400mm - diameter 80mm; d) distance 400mm - diameter 135mm
Figure 4.10.: IAS AC encoder 1000ppr vs TVM, 2 cycles at: a-b) 150rpm; c-d) 450rpm; e-f) 1500rpm, 50Hz line. b,d,f) are filtered
Figure 4.11.: IAS encoder (ET 1000ppr) vs TVM signal, 1500rpm 50Hz without inverter.

Figure 4.12.: IAS encoder (ET 1000ppr) vs TVM signal, 1500rpm 50Hz without inverter. Signal filtered
4.1.3. IAS compared to Acceleration

In this test, acceleration measurements are compared to the Instantaneous Angular Speed measurement. In order to compare the measurements from the encoder and the accelerometer, an order analysis is required. So, in order to visualize the results, the order domain is chosen. The encoder signal is already in the proper domain, while the accelerometer output needs an angular resampling. The IAS processing is done as described in the previous chapters. The acceleration data is angular resampled using the Index pulse as the reference for the signal processing. The speed between two pulses is considered constant and uniform spacing is applied between a certain number of intermediate points selected for angular resampling. Then an FFT processing is applied, obtaining the acceleration spectrum in order domain.

The motor under test has a working history. The characteristic frequencies of the installed bearing (type 6204-2RS1) are listed in Table 4.1. The comparison presents the IAS orders obtained with the ET of the 1000ppr encoder signal and the accelerometer signals resampled at 1000ppr. The encoder signal shows that at low orders, the signal is good, while at higher order there is a quantization error, [9]. The higher the speed, the bigger the quantization effect.

The order analysis from the IAS and the accelerometer data displays similar sidebands in the low order region. Figures 4.13-4.15 depict IAS plots from the encoder data in the first subplot, while in the following three, the acceleration data in the three directions are reported. Fig. 4.13(a) presents the measurement from 0 to the maximum order (500), while Fig. 4.13(b) zooms from 0 to the 10 order. The encoder’s main orders are 1, 2, 4.008, while the acceleration’s main orders are 1, 4.008 and 8.016. Fig. 4.14 zooms around the fourth order where the 4.008 order appears in all the signals. All the peaks are surrounded by sidebands at 0.008. These are more evident at higher orders, especially in the accelerometer data. The IAS also shows sidebands at the FTF order 0.382. The same sidebands are present in the accelerometer data, but at higher orders and the peaks are smeared. Other sidebands are present at the order 0.064. These are related to the number of rotor bars, \( R = 32 \). Fig. 4.15 zooms around the 8 order. The 8.016 order is shown and sidebands at 0.008. The sidebands at 0.064 are not symmetrical.

4.1.4. Unbalance test

Another test is carried out with Experimental Test Setup number 1: the application of a small mass in order to create an overhung unbalance configuration. The coupling connecting the motor and the encoder is held in position by means of three bolts. One of these is substituted with a different one having a bigger mass. The equivalent concentrated unbalance mass is 2.65g, located at 24.6mm from the shaft centerline, giving 65g-mm and the coupling radius is 20mm. The result is shown in Fig. 4.16

A variation in the amplitude of the IAS spectrum is obtained, showing the capability of this measurement to also detect a variation in the balancing conditions. This kind of unbalance is usually seen as a peak at order 1x in the radial and axial directions of the vibration spectrum. In this situation, the variation of the air-gap length between the rotor and the stator creates a sort of eccentricity, producing a variation of electrical higher orders seen in the IAS measurement.

The order 4.008x presents a bigger amplitude due to this electromagnetic effect. The same behaviour is shown in Fig. 4.17, where the measurements of ETR2 and ETR3 are reported in the no load condition, probably due to the new alignment.
Figure 4.13.: IAS and accelerometer order analysis. The first subplot represents the encoder data, while the three below these are the accelerometer data in the X, Y, and Z directions. a) full scale plot, 0-500 order; b) zoom plot 0-10 order

Figure 4.14.: IAS and accelerometer order analysis. The first subplot represents the encoder data, while the three below these are the accelerometer data in the X, Y, and Z directions. a) zoom plot, 3.5-4.5 order; b) zoom plot 3.9-4.1 order
Figure 4.15.: IAS and accelerometer order analysis. The first subplot represents the encoder data, while the three below these are the accelerometer data in the X,Y, and Z directions. a) zoom plot, 7.5-8.5 order; b) zoom plot 7.75-8.25 order

Figure 4.16.: IAS encoder, ET 1000ppr, 1500rpm 50Hz without inverter. With and without unbalance
Figure 4.17.: ETR2 and ETR3 in the no load condition: same amplitude at order 3 but different at order 4.008
4.2. Experimental Test Rig - 2

The motor adopted for the test is an ELETTRONICA SANTERNO MJ 90 LA 4 B3 02/07, 1.5kW 4 poles electric induction motor, driven by a 380V, 50Hz line current, Fig. 4.18. The motor’s specifications are reported in Table 4.2 4.3 4.4. The encoder installed (Not Driving End NDE) is a TEKEL TSW80P with 1024 pulses per revolution (ppr) and its shaft is rigidly connected to the rotor, while the encoder’s case is fixed at the stator through a joint, Fig. 4.19. The motor is provided of a fan with 7 blades made in fiber reinforced plastic. In this setup there are also installed: a torquemeter, a magnetic brake and a fly-wheel.

<table>
<thead>
<tr>
<th>$P_n$ [kW]</th>
<th>$N_n$ [rpm]</th>
<th>$T_n$ [Nm]</th>
<th>$I_n$ 400V [A]</th>
<th>$\cos \phi$</th>
<th>$\mu$ [%]</th>
<th>$J$ [kg m²]</th>
<th>$m$ [kg]</th>
<th>S</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1390</td>
<td>10.3</td>
<td>3.52</td>
<td>0.78</td>
<td>78.6</td>
<td>0.0035</td>
<td>14</td>
<td>24</td>
<td>22</td>
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</table>

Table 4.3.: Characteristic orders, bearing 6205-ZZ

<table>
<thead>
<tr>
<th>Defect</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass Pass Frequency - Inner</td>
<td>BPFI</td>
</tr>
<tr>
<td>Bass Pass Frequency - Outer</td>
<td>BPFO</td>
</tr>
<tr>
<td>Fundamental Train Frequency (Cage)</td>
<td>FTF</td>
</tr>
<tr>
<td>Ball Spin Frequency (Rolling element)</td>
<td>BSF</td>
</tr>
<tr>
<td>Rolling element defect frequency</td>
<td>RDF</td>
</tr>
</tbody>
</table>

Table 4.4.: Bearing 6205, various brand

<table>
<thead>
<tr>
<th>Bearing</th>
<th>BPFI</th>
<th>BPFO</th>
<th>FTF</th>
<th>BSF</th>
<th>RDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKF 6205 F</td>
<td>5.427</td>
<td>3.573</td>
<td>0.397</td>
<td>2.325</td>
<td>4.65</td>
</tr>
<tr>
<td>SKF 6205 QE6</td>
<td>5.434999</td>
<td>3.565</td>
<td>0.395999</td>
<td>2.3025</td>
<td>4.605</td>
</tr>
<tr>
<td>NTN 6205 F</td>
<td>5.416</td>
<td>3.584</td>
<td>0.398</td>
<td>2.355</td>
<td>4.71</td>
</tr>
<tr>
<td>NSK 6205 F</td>
<td>5.434999943</td>
<td>3.565000057</td>
<td>0.395999998</td>
<td>2.30250001</td>
<td>4.605000019</td>
</tr>
<tr>
<td>FAG 6205 F</td>
<td>5.433</td>
<td>3.567</td>
<td>0.396</td>
<td>2.309</td>
<td>4.618</td>
</tr>
</tbody>
</table>

4.2.1. Measurements ETR2

The first test is the measurement of the IAS with (256ppr - ETD method) and without (1024ppr - ET method) decimation, Fig. 4.20 using the 50Hz power line at three different loads:
- no load (2.17A RMS)
- 2.60Nm RMS (2.27A RMS)
- 6.16Nm RMS (2.75A RMS)

The computed IAS spectrum is reported in Fig. 4.21 4.22 for the two counting configurations. The plots show the behaviour due to the slip seen in Sect. 4.1.1. Fig. 4.23 shows the application of a high pass filter in order to remove the DC component of the signal. The result at higher orders is the same. Fig. 4.24 shows the variation of the signal while the load is decreased from the maximum torque to the no load condition. In Fig. 4.21 4.22, peaks are present at FTF orders of the bearings, like in [75].
Figure 4.18.: Experimental test rig - 2

Figure 4.19.: TEKEL TSW80P encoder and 7 blade fan
Figure 4.20.: Measurements of ETR2 in three loading conditions, 1024ppr ET method and 256ppr ETD method: a) range $0 \div 12 \cdot 10^5$ samples; b) range $0 \div 10000$ samples
Figure 4.21: IAS spectrum processing the signal from the 1024ppr ET method
Figure 4.22.: IAS spectrum processing the signal from the 256ppr ETD method
4.2. Experimental Test Rig - 2

Figure 4.23.: The figure presents the filter effect, setting the high-pass at 0.01 order versus 0.1 order. Peaks at order 0.007 and 0.034 are present in the former case, while with the filter at higher order, the first peak disappears.

Figure 4.24.: IAS signal in angle domain and in order domain during a load variation. Note the smearing of the peaks related to the slip.
4.2.2. Characteristic orders in the IAS spectrum

Magneto-motive force (MMF) space harmonics

The current flowing into the stator of an IM generates an electromagnetic excitation which consists in an infinite number of harmonic MMFs changing in time according to \( \cos(\omega t) \) and in space according to \( \cos(\nu p \theta_s) \). A three-phase \((m = 3)\) ideal motor with balanced sinusoidal currents is considered. Three windings are shifted in space by \(2\pi/3\) electrical degrees. Three input currents are injected into the stator with theoretically the same amplitude and the same phase shift equal to \(2\pi/3\) electrical degrees. This generates a total MMF of:

\[
F_1(\theta_s, t) = \sum_{\nu} F_{m\nu} \cos[(2\pi f)t + (\nu p)\theta_s] = \sum_{\nu} F_{m\nu} \cos[(\nu p)\theta_s + (2\pi f)t]
\]  

(4.12)

with:

\[
\nu_+ = 2km + 1 \quad \nu_- = 2km - 1 \quad \nu = 2km \pm 1
\]  

(4.13)

or using another notation [44],

\[
\nu = 2gm + 1 \quad g = 0, \pm 1, \pm 2, \ldots \quad \nu = 1, -5, 7, -11, 13, \ldots
\]  

(4.14)

\[
F_1(\theta_s, t) = \sum_{\nu} F_{m\nu} \cos[(2\pi f)t - (\nu p)\theta_s] = \sum_{\nu} F_{m\nu} \cos[(\nu p)\theta_s - (2\pi f)t]
\]  

(4.15)

In this specific case (three-phase stator winding), the harmonics present in the spectrum \(\nu = mk\) with \(k = 1, 3, 5, \ldots\) do not exist. The forward-rotating harmonics \(\nu_+ = 1, 7, 13, 19, \ldots\) are the arithmetic sum of waves in all three phases, while the backward-rotating harmonics \(\nu_- = 5, 11, 17, 23, \ldots\) are zero [33]. \(\nu = 5, 7\) are a consequence of trapezoidal phase MMF shape [44]. IM are characterized by the presence of the slip \(s\). This parameter is correlated to the load/speed of the machine. At the motor’s startup the slip is 1, at no load is 0, with load \(0 < s < 1\). Other slip-dependent parameters are defined in Table 1.1. The magnetic flux in the rotor and in the stator are running with the same synchronous speed \(n_s\), since \(n_s = n_s(1 - s) + s n_s\). Considering a constant fundamental frequency, the current in the stator completes a revolution in \(\theta_s\), while the rotor does it in \(\theta_m\) (with \(\tau_s \neq \tau_m\)) owing to the slip. The encoder senses this latter speed. The Eq. 4.15 describes the MMF with a periodicity of

\[
w_\nu = 0, 12, 12, 24, 24, 36, 36, \ldots \quad \text{for} \quad \nu = 1, -5, 7, -11, 13, -17, 19, \ldots
\]  

(4.16)

while in the IAS spectrum these orders can be found at \(o_\nu\), Eq. 4.17. This equation does not take into account the fundamental frequency because it does not have an influence on the generated periodicity.

\[
o_\nu = \frac{p}{1 - s} (\nu - 1)
\]  

(4.17)

In Table 4.5 the harmonics generated in IAS spectrum by the MMF space harmonics are reported \((\nu = -20, -1, \ldots, 1, 20\) in order to consider a not ideal machine). Note that \(\nu = -5, 7\) have the same absolute value \(o_\nu = 12.425, \nu = 3, 9, 15, \ldots\) can be correlated to stator eccentricity, while even space harmonics are due to mechanical unbalance. These harmonics exactly excite the frequencies found calculating stator and rotor combinations [86]

\[
o_\nu = 0, 4.142, 8.283, 12.425, 16.566, 20.708, 24.849, 28.991, 33.132, \ldots
\]  

(4.18)
Table 4.5.: Current harmonic frequencies, \((p = 2, s = 0.03417)\)

<table>
<thead>
<tr>
<th>(\nu)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(o_\nu)</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>(\nu)</td>
<td>10.3538</td>
<td>12.4245</td>
<td>14.4953</td>
<td>16.5661</td>
<td>18.6368</td>
</tr>
<tr>
<td>(o_\nu)</td>
<td>20.7076</td>
<td>22.7783</td>
<td>24.8491</td>
<td>26.9199</td>
<td>28.9906</td>
</tr>
<tr>
<td>(\nu)</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>(o_\nu)</td>
<td>31.0614</td>
<td>33.1321</td>
<td>35.2029</td>
<td>37.2736</td>
<td>39.3444</td>
</tr>
<tr>
<td>(\nu)</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
<td>-4</td>
<td>-5</td>
</tr>
<tr>
<td>(o_\nu)</td>
<td>-4.1415</td>
<td>-6.2123</td>
<td>-8.2830</td>
<td>-10.3538</td>
<td>-12.4245</td>
</tr>
<tr>
<td>(\nu)</td>
<td>-6</td>
<td>-7</td>
<td>-8</td>
<td>-9</td>
<td>-10</td>
</tr>
<tr>
<td>(o_\nu)</td>
<td>-14.4953</td>
<td>-16.5661</td>
<td>-18.6368</td>
<td>-20.7076</td>
<td>-22.7783</td>
</tr>
<tr>
<td>(\nu)</td>
<td>-11</td>
<td>-12</td>
<td>-13</td>
<td>-14</td>
<td>-15</td>
</tr>
<tr>
<td>(\nu)</td>
<td>-16</td>
<td>-17</td>
<td>-18</td>
<td>-19</td>
<td>-20</td>
</tr>
<tr>
<td>(o_\nu)</td>
<td>-35.2029</td>
<td>-37.2736</td>
<td>-39.3444</td>
<td>-41.4152</td>
<td>-43.4859</td>
</tr>
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</table>

Table 4.6.: IAS current harmonic frequencies \(o_\nu\), \((p = 2)\)

<table>
<thead>
<tr>
<th>(s)</th>
<th>0.00088</th>
<th>0.00175</th>
<th>0.01466</th>
<th>0.03417</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu = 11, -9)</td>
<td>±20.0176</td>
<td>±20.0351</td>
<td>±20.2976</td>
<td>±20.7076</td>
</tr>
</tbody>
</table>

**Time harmonics and other frequencies**

In the bibliography, it is suggested to analyze the second time harmonic in the frequency spectrum. This allows to detect current supply unbalance as suggested in [70, 75, 33, 19]:

\[
f_r = 2f
\]

that, for a 50Hz supply frequency, is:

\[
f_r = 2 \cdot 50 = 100Hz
\]

the existence of this frequency component could also be due to by the presence of the MMF space harmonic \(\nu = 3\):

\[
f_r = 2f = o_3 n_m
\]

with, Eq. 4.17:

\[
o_3 = \frac{p}{1 - s} (3 - 1) = \frac{2p}{1 - s}
\]

and:

\[
f_r = 2f = o_3 n_m = \frac{2p}{1 - s} \frac{1 - s}{p} f = 2f
\]

The consequence is that, in the IAS spectrum, the 100Hz in frequency spectrum seen in MCSA corresponds to the IAS’ order 4.1415 for a four-pole motor with a 50Hz supply frequency and slip \(s = 0.03417\). Instead, the time harmonic \(f_r = 3f\) (seen in MCSA) is related to the motor’s saturation and other causes [88].
Figure 4.25.: Harmonics in IAS spectrum, TR (only motor) and EL configuration \(s_1 = 0.00088, s_2 = 0.00175, s_3 = 0.01466, s_4 = 0.03417\), orders 0-50
Figure 4.26.: Harmonics in IAS spectrum, TR (only motor) and EL configuration ($s_1 = 0.00088$, $s_2 = 0.00175$, $s_3 = 0.01466$, $s_4 = 0.03417$), orders 0-14
Figure 4.27.: Harmonics in IAS spectrum, TR (only motor) and EL configuration (s₁ = 0.00088, s₂ = 0.00175, s₃ = 0.01466, s₄ = 0.03417), orders 24-30
Figure 4.28.: MMF harmonics in the IAS spectrum, TR (only motor) and ETR2 configuration ($s_1 = 0.00088$, $s_2 = 0.00175$, $s_3 = 0.01466$, $s_4 = 0.03417$)
**Experimental test** Figures 4.25-4.27 show the IAS measurement of the same motor in two different experimental configurations:

- motor only (no load), called TR
- ETR2 (three loads) [76, 75]

In the ETR2 case, there is a strong component owing to unbalanced currents or stator eccentricity. In this specific case it is probably related to the eccentricity because the experimental setup ETR3, with the same motor and a stiffer coupling that fixed the rotor in a better position, shows a lower amplitude of the MMF space harmonic $\nu = 3$. Order 3 keeps the same amplitude through the various measurements, so it is an indicator of the measurement quality. Sidebands are present around these orders at $2ps$. The IAS spectrum of the induction motor can be divided into two zones:

- orders 0-16: current space and time harmonics effect
- orders 16-40: rotor/stator slotting, skewness effect, saturation

In Table 4.6, the calculation of $o_\nu$ (Eq. 4.17) is extended to the four different configurations of slip ($s = 0.00088, 0.00175, 0.01466, 0.03417$). In Fig. 4.28 these orders are highlighted.

**Rotor influence**

The conductors (bars) are often skewed slightly along the length of the rotor to reduce noise and smooth out torque fluctuations that might result at some speeds due to interactions with the pole pieces of the stator, Fig. 4.29. In Fig. 4.30, a phenomenon correlated to the rotor skewness is present. This effect can be seen in those orders integer order + $2ps$ with sidebands. The latter can be calculated with Eq. 4.24. In Fig. 4.7 these sidebands are calculated for two different motors. The first involved in the experiment has a skew of 1 bar. The value of $o_\nu$ is very close to the experimental value 0.282. Considering geometric tolerances, the value 1.033 can be assigned to the skewness parameter $sk$. Sidebands are also present in the second motor, but further investigation is necessary because it has $R = 32$ and $sk = 1.5$, so the result is $o_{sk} = 0.2813$, Fig. 4.7.

The physical explanation of these sidebands is very simple: at every integer order, the rotor feels electromagnetic pull (main order correlated with $2ps$) and owing to the presence of skewness, the number of pole pairs, the number of phases and the number of rotor bars, a modulation around the main order appears. If confirmed, it may be a very interesting result because this effect probably cannot be seen in MCSA due to the smearing of the peaks. The IAS spectrum, being fixed with the rotor, allows this kind of information extraction.

\[
o_{sk} = \frac{pm}{R} sk
\]  
(4.24)

<table>
<thead>
<tr>
<th>$R$</th>
<th>22</th>
<th>22</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>$sk$</td>
<td>1.033</td>
<td>1.033</td>
<td>1.5</td>
</tr>
<tr>
<td>$o_{sk}$</td>
<td>0.2727</td>
<td>0.2817</td>
<td>0.2813</td>
</tr>
</tbody>
</table>

**Figure 4.29.: Rotor skewness**
Figure 4.30: Rotor skewness harmonics in the IAS spectrum. TR (only motor) and ETR2 configuration ($s_1 = 0.00088$, $s_2 = 0.00175$, $s_3 = 0.01466$, $s_4 = 0.03417$)
4.3. Experimental Test Rig - 3

Experimental test rig (ETR3) uses the same motor and the same encoder used in ETR2. The experimental test rig is developed to evaluate different bearing conditions and load influences on the IAS measurements. The setup consists of the motor, a shaft supported by three bearings (inline) and a synchronous generator to provide the requested load. The bearing are the same (UC201 or YAR 203/12-2F), but the centre one could be removed and replaced with a faulty one (BPFI inner ring fault). The characteristic frequencies are reported in Table 4.8. In Fig. 4.31(b), the replacement phase is shown. Note that the alignment between the electrical motor and the bearing system does not change during this phase because the shaft could be extracted and reinstalled simply unscrewing the coupling bolts. The load is generated by a synchronous generator provided with a rheostat. A variable torque is obtained by tuning the resistance value. Voltage and current probes calculate the exact power absorbed by the motor and the brake, and is calculated as:

\[
P = VI = RI^2 = V^2/R \quad [W]
\]  \hspace{1cm} (4.25)

Current (Fluke i310s) and Voltage (Elditest GE8115) clamps are used to acquire the signals. The measurement range settings of i310s are: 30A (sensibility 10mV/A) or 300A (sensibility 1mV/A). The frequency range is up to 20kHz. Two triaxial PCB 356A16 (10.2mV/(m/s²)) accelerometers are used.

Table 4.8.: Characteristic orders, bearing UC201 (YAR 203/12-2F)

<table>
<thead>
<tr>
<th>Defect</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass Pass Frequency - Inner</td>
<td>BPFI</td>
</tr>
<tr>
<td>Bass Pass Frequency - Outer</td>
<td>BPFO</td>
</tr>
<tr>
<td>Fundamental Train Frequency (Cage)</td>
<td>FTIF</td>
</tr>
<tr>
<td>Ball Spin Frequency (Rolling element)</td>
<td>BSF</td>
</tr>
<tr>
<td>Rolling element defect frequency</td>
<td>RDF</td>
</tr>
</tbody>
</table>

4.3.1. Dynamic characterization

Natural frequencies of the experimental test rig 3 (ETR3) are investigated through FRF impact testing in order to gain a better knowledge of the system. The system components are installed one by one and after each single installation an FRF impact test is carried out. Many measurement points are considered. The points considered are located on the base (points 1,2) and on the motor (points 3,4), Fig. 4.32. An LMS TestXpress data acquisition system is adopted for the measurement, using an hammer with a load sensor and some accelerometers from PCB. The location of force application and the reading points are reported in the graph’s legend.

Fig. 4.35(a) displays a resonance at 300Hz located in the motor’s shield, response point 3. The response at point 1 is less affected by this resonance (Fig. 4.35(b)), nevertheless this frequency can be heard when the motor is running, so further test considered the shield removal. Fig. 4.35(c) 4.35(d) report the FRF impact test while the motor is running. Peaks due to electromagnetic noise are present at 650Hz, with 25Hz sidebands. These are investigated in the Sect. 1.2.

In the FRFs natural frequencies at 40Hz, 180Hz, 236Hz, 300Hz, 571Hz (points 3,4), 688-716-727Hz (point 3), 744Hz, 900Hz, 953Hz are present. The direct response at point 1 emphasizes the frequencies 236Hz and 744Hz. While at point 3, 300Hz and 727Hz are dominant. Frequencies 236Hz e 744Hz are considered as natural frequencies of the base.
Figure 4.31.: Experimental test rig - 3: a) electrical motor, bearings, brake and sensors (incremental encoder with 1024 ppr); b) positioning system; c) damaged bearing

**Changing the system configuration**

The bearing base is added to the system, Fig. 4.36(a). Fig. 4.36(a)-4.36(d) show different tightening torque of the bolts (35-45Nm) and plate’s location (115,125,135mm). The tightening torque does not affect the performance of the system, while the changing of the plate’s location moves the base’s natural frequencies from 236Hz to 251Hz, from 571Hz to 526Hz and from 727Hz to 755Hz. A new peak appears at 805-812Hz and it is the most influenced one owing to the various settings.
The brake is added in Fig. 4.36(e)-4.36(f). The FRFs change 180Hz → 154Hz, 300Hz → 201Hz, and the frequencies 744Hz and 802Hz get close showing only one peak. The peaks at 331Hz and 539Hz are dominant in the spectrum.
**FFT during operation**

The motor is tested in both directions FWD and RWD acquiring the FFTs from the response points Fig. 4.34. with and without the shield. The accelerometer is also located on the encoder’s body. Other measurements are taken with the motor unbolted and positioned on a rubber sheet. The results are plotted in Fig. 4.37. There is a significant difference in signal amplitude at different points.

![Image of FFT test setup, motor only](image1)

*Figure 4.32.: FRFs test setup, motor only*

![Image of changing system configuration](image2)

*Figure 4.33.: Changing the system configuration*
Figure 4.34.: FFTs testing during motor operation

Figure 4.35.: a) the system with the motor only, FRF channel 3 direction Y, with and without the damping added; b) the system with the motor only, FRF channel 1 direction Y, with and without the damping added; c) the system with the motor only, FRF channel 1 direction Y, with the motor turned on and off; d) the system with the motor only, FRF channel 3 direction Y, with the motor turned on and off.
Figure 4.36.: FRFs: a) 35Nm - 125mm; b) 45Nm - 125mm; c) 35Nm - 115mm; d) 35Nm - 135mm; e) 35Nm - 125mm, with brake 60mm; f) 35Nm - 125mm, with brake 70mm
Figure 4.37.: FFTs: (a-c) X direction; (d-f) Y direction; (g-i) Z direction
4.3.2. Test configuration

A test able to acquire many sources of different typology is carried out in order to understand the IAS capability of detecting simple faults in a system. The multi measurements approach allows to understand a phenomenon from different points of view, confirming a certain system’s behaviour.

Measurements are, Fig. 4.31:
- accelerometer 1 (tri axial), located on the test bearing
- accelerometer 2 (tri axial), located on the motor
- voltage 1, located on the motor
- voltage 2, located on the generator
- current 1, located on the motor
- current 2, located on the generator
- IAS from encoder

Four different working conditions are selected in order to see which orders/frequency are moving with the load due to the slip effect. Two of them have a fault in the inner race ring of the central bearing (BPFT). Note that the bearing is not radially loaded. The noise generated by the faulty bearing is in the audible range but temperatures are constant at $30^\circ \div 35^\circ C$, with an external temperature of $25^\circ C$. The motor is running perfectly (no variations in voltage and current values) even with the faulty bearing installed, but acceleration values are high.

The configurations are:
A no load - no fault
B load - no fault
C no load - fault
D load - fault

Table 4.9 collects some statistical values from the various measurements:
- Mean
- Median
- Root Mean Squared (RMS)
- Peak2peak
- Peak2rms
- Kurtosis
- Skewness

The results are discussed in the next sections.

**Bearing damage** The bearing is artificially damaged in order to simulate the aging effect. Common damaging techniques use electro discharge machining or chemical corrosion. In this PhD thesis, the damage is created using an high speed rotary tool, Fig. 4.38. The 2mm tip tool grinds the material without generating sharp edges. The defect is located on the inner rail of the bearing, Fig. 4.39. The simulated damage depthness is very close to the deepness of a real damaged bearing, Fig. 4.39(b)
Figure 4.38.: Bearing damaging technique using an high speed rotary tool with 2mm tip

Figure 4.39.: Bearing damage: a) the damaging method adopted in this PhD thesis; b) a real bearing damaged; c) outer ring race of the tested bearing
Table 4.9.: ETR3 measurements, statistical values (3 seconds acquisition). Accelerations in m/s², Voltages in V, Currents in A. Measurement: A) no load - no fault; B) load - no fault; C) no load - fault, D) load - fault.

<table>
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<th>Channel</th>
<th>Meas</th>
<th>Mean</th>
<th>Median</th>
<th>Rms</th>
<th>Peak2peak</th>
<th>Peak2rms</th>
<th>Kurtosis</th>
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<td>5.620</td>
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<td>-1.743</td>
<td>231.488</td>
<td>613.718</td>
<td>1.326</td>
<td>1.392</td>
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<td>-1.751</td>
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<td>615.752</td>
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<td>-0.030</td>
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<td>Volt 2</td>
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<td>-0.043</td>
<td>0.050</td>
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<td>-0.020</td>
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<td>0.513</td>
<td>0.514</td>
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<td>1.275</td>
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</table>
4.3.3. Acceleration

Considering measurement amplitudes shown in Table 4.9 the accelerometer located on the faulty bearing is the most significant. The Root Mean Squared (RMS) value is bigger in X and Y directions, while the Kurtosis value is predominant in the radial (Z) direction. Figure 4.40 confirms this consideration. X and Y directions show a periodicity of 0.042s, that equals the mechanical speed \( n_m \) and, while with the faulty BPFI bearing, they also show a modulation of 0.412s (2.4272 Hz). The direction Z shows the peaks at the mechanical speed and the modulation is less pronounced.

After applying the FFT processing, Fig. 4.42 is obtained. The system has a frequency content up to 10000Hz. Zooming in at the same plot with an y axis scale up to 0.4m/s², Fig. 4.43 shows the difference at hi-frequency when the faulty bearing is present (C,D configurations). There is a peak at 20000Hz that should be the accelerometer’s resonance. Usually this frequency region is selected for the envelope analysis processing (of the acceleration signal). Looking at the spectrum up to 4000Hz (Fig. 4.44), the maximum peak can be found in the Y direction. The BPFI fault generates peaks at:

\[
 f_{BPFI} = k n_m BPFI \quad \text{with} \quad k = 1, 2, 3, \ldots \tag{4.26}
\]

and every peak has many sidebands at:

\[
 f_{BPFI, std} = \pm z n_m \quad \text{with} \quad z = 1, 2, 3, \ldots \tag{4.27}
\]

in our system, sideband harmonics can be seen up to \( z = 8 \). This phenomenon results in a very close superposition of harmonics resulting in the beating frequency 2.384Hz \( \approx 2.4272 \)Hz. The theoretical BPFI value of the bearing installed is, Table 4.8:

\[
 BPFI = 4.947
\]

Considering the configuration C in Fig. 4.45. two peaks can be selected:

\[
 f_{C1} = 1194.7632Hz \quad f_{C2} = 1243.505Hz
\]

\[
 f_{C21} = f_{C2} - f_{C1}
\]

\[
 BPFI = \frac{2f_{C1}}{10f_{C21}} = 4.9024 \tag{4.28}
\]

\[
 n_m C = \frac{f_{C21}}{2} = 24.3709Hz \tag{4.29}
\]

where \( f_{C1} \) is the peak owing to the 10x BPFI frequency and \( f_{C2} \) is the sidebands at twice the mechanical speed \( n_m \). And considering the configuration D:

\[
 f_{D1} = 1184.665Hz \quad f_{D2} = 1233.0055Hz
\]

\[
 n_m D = \frac{f_{D2}}{2 + 10 \cdot BPFI} = 24.1651Hz \tag{4.30}
\]

The real value of BPFI is 4.9024. The Fig. 4.46 shows the effect of electromagnetic forces generated by the motor. The BPFI sidebands can be also seen in this frequency range.
4.3.4. Voltage and Current

Figure 4.41 shows voltages and currents acquired in two locations, at the induction motor mains and at the synchronous generator output. The induction motor signal shows a periodicity of 0.0205s (48.78Hz ≈ 50Hz), the supply frequency, and no variation is shown between the different working conditions. The output signal of the generator shows a variable periodicity of 0.0011s (900Hz) in the loaded conditions while it is equal to zero in the no load conditions. The current plot shows the same behaviour as the voltage.

After the FFT processing, volt 1 shows the main peak at 48.83Hz and the harmonics at:

<table>
<thead>
<tr>
<th>f</th>
<th>3f</th>
<th>5f</th>
<th>7f</th>
<th>9f</th>
<th>11f</th>
<th>13f</th>
<th>15f</th>
<th>17f</th>
<th>19f</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.83</td>
<td>146.49</td>
<td>244.15</td>
<td>341.81</td>
<td>439.47</td>
<td>537.13</td>
<td>634.79</td>
<td>732.45</td>
<td>830.11</td>
<td>927.77</td>
</tr>
</tbody>
</table>

In the spectrum, these frequencies are not influenced by the slip, while other frequency are related to the load, Fig. 4.47. There are also components at these frequencies plus twice the mechanical speed. There is no difference between the healthy and faulty condition when considering these measurements. The current shows the same pattern as voltage, Fig. 4.48. Note the sidebands around the fundamental frequency. The bearing fault does not induce any major change in the spectrum as in the acceleration signal.

The synchronous generator presents lots of harmonics. The main peak is at 869.274Hz with sidebands at 144.386Hz and each one of these peaks have sidebands at the mechanical speed. Voltage and current show a similar behaviour in case of load, while, under no load, the information is absent in the current channel but the voltage probe shows an interesting change probably owing to the bearing fault, Fig. 4.49. Note that this output was originally selected only for measuring the output power. The triangular shape could be generated from the internal rectifier that converts the alternate current to continuous current. So further analysis should be conducted with this signal.

Frequencies produced by the synchronous generator can be found in the acceleration and the IAS measurements (Fig. 4.44, Fig. 4.51 Fig. 4.53). Table 4.11 shows acceleration peaks in frequency domain and the respective orders in IAS spectrum. The mechanical speed $n_m$ can be calculated from these frequencies, but the FFT’s resolution affects the estimation of the speed.

<table>
<thead>
<tr>
<th>Freq Hz</th>
<th>845.3</th>
<th>869.5</th>
<th>893.6</th>
<th>917.7</th>
<th>941.8</th>
<th>966.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order IAS</td>
<td>35</td>
<td>36</td>
<td>37</td>
<td>38</td>
<td>39</td>
<td>40</td>
</tr>
</tbody>
</table>
4.3.5. IAS analysis

One of the most important features of IAS is that information is contained in one signal only. In the previous section, it has been shown how the encoder feels the presence of the generator and its change with working conditions. In this section the most important result is that the IAS is able to detect a BPFI fault in a bearing located outside the motor!

Figure 4.52 depicts the IAS spectrum in four different conditions (A,B,C,D). The IAS spectrum varies little in respect to acceleration, but it changes more than the current and voltage signals. New peaks can be seen in the zone from order 20 to order 30 (the motor’s saturation zone and the harmonics 11-13 of the supply frequency).

This can be very interesting because, considering the size of the fault in the bearing, the IAS spectrum could be used as an end of life indicator: the acceleration and its various processing techniques are too sensitive and they can detect the fault presence well before the industrial needs. For example, the envelope analysis can detect a bearing fault at least from 6 month to one year before the effective maintenance of a certain piece of equipment. The IAS could be used in order to set the other measurement thresholds.

In order domain, the BPFI should be located at:

\[ o_{BPFI} = BPFI = k \cdot BPFI \quad \text{with} \quad k = 1, 2, 3, \ldots \]  \hspace{2cm} (4.31)

and sidebands at:

\[ o_{BPFI_{sid}} = \pm g \quad \text{with} \quad g = 1, 2, 3, \ldots \]  \hspace{2cm} (4.32)

Three measurements are done for every condition using this experimental test ETR3, so a total amount of 12 measurements. The real BPFI value changes during the same working condition as:

\[ BPFI = 4.9034 \div 4.9038 \]  \hspace{2cm} (4.33)

and the resulting harmonics:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
</table>

The modulation of the signal is due to:

\[ [(BPFI \cdot order_i) - \text{integer}_A] - [(BPFI \cdot order_{i-1}) + \text{integer}_B] \]  \hspace{2cm} (4.34)

\[ [(4.9036 \cdot 6) - 2] - [(4.9036 \cdot 5) + 3] = -0.0964 \]

\[ [(4.9036 \cdot 6) - 3] - [(4.9036 \cdot 5) + 2] = -0.0964 \]

\[ [(4.9036 \cdot 6) - 4] - [(4.9036 \cdot 5) + 1] = -0.0964 \]

\[ [(4.9036 \cdot 6) - 1] - [(4.9036 \cdot 5) + 4] = -0.0964 \]
and the mechanical speeds can be recalculated as, Eq. 4.30:

\[ n_{m_C} = \frac{1243.505}{2 + 10 \cdot 4.9036} = 24.3653 \text{Hz} \]  \hspace{1cm} (4.35)

\[ n_{m_D} = \frac{1233.0055}{2 + 10 \cdot 4.9036} = 24.1595 \text{Hz} \]  \hspace{1cm} (4.36)

resulting in:

\[(BPFI \cdot order_i) - integer_A] - [(BPFI \cdot order_{i-1}) + integer_B] \cdot n_m \]  \hspace{1cm} (4.37)

\[(4.9036 \cdot 6) - 2] - [(4.9036 \cdot 5) + 3] \cdot 24.1595 = -2.3290 \text{Hz} \]

\[(4.9036 \cdot 6) - 3] - [(4.9036 \cdot 5) + 2] \cdot 24.1595 = -2.3290 \text{Hz} \]

\[(4.9036 \cdot 6) - 4] - [(4.9036 \cdot 5) + 1] \cdot 24.1595 = -2.3290 \text{Hz} \]

\[(4.9036 \cdot 6) - 1] - [(4.9036 \cdot 5) + 4] \cdot 24.1595 = -2.3290 \text{Hz} \]

The frequencies in the acceleration spectrums and the orders in the IAS spectrum perfectly match these values, Fig. 4.54. The IAS has the advantage of keeping the BPFI frequencies at the same location when the load changes, except the above mentioned small variations owing to mechanical tolerances. This is useful when an automated procedure is used to detect the BPFI fault. In Fig. 4.55 are plotted the same BPFI harmonics:

\[ ((BPFI \cdot order_{i-1}) + integer) \quad order_{i-1} = 5 \quad integer = 2 \]  \hspace{1cm} (4.38)

\[ (BPFI \cdot 5) + 2 \]  \hspace{1cm} (4.39)

\[ (4.9036 \cdot 5) + 2 = 26.5180 \]

supposing the sidebands at:

\[ \pm 0.0964 \]

and:

\[ ((BPFI \cdot 5) + 2) \cdot n_{m_C} \]  \hspace{1cm} (4.40)

\[ [(4.9036 \cdot 5) + 2] \cdot 24.3653 = 646.1190 \]

supposing the sidebands at:

\[ \pm 2.3488 \]

and:

\[ ((BPFI \cdot 5) + 2) \cdot n_{m_D} \]  \hspace{1cm} (4.41)

\[ [(4.9036 \cdot 5) + 2] \cdot 24.1595 = 640.6616 \]

supposing the sidebands at:

\[ \pm 2.329 \]

so, they are not sidebands one in respect to the other, but one in respect to BPFI main peaks!
Figure 4.40.: Acceleration signals, position 1, three directions and four conditions (A,B,C,D).

Figure 4.41.: Voltage and Current: a,c) pos 1, induction motor; b,d) pos 2, synchronous generator.
Figure 4.42.: Acceleration signals, position 1, three directions.
Figure 4.43.: Acceleration signals, position 1, three directions.
Figure 4.44.: Acceleration signals, position 1, three directions. Zoom 0-4000Hz.
Figure 4.45.: Acceleration signals, position 1, three directions. Zoom 1000-1500Hz.
Figure 4.46.: Acceleration signals, position 1, three directions. Zoom 500-700Hz.
Figure 4.47: Voltage 1 signal.
Figure 4.48.: Current 1 signal.
Figure 4.49.: Voltage 2 signal.
Figure 4.50.: Current 2 signal.
Figure 4.51.: Generator harmonics in the acceleration signals.
Figure 4.52.: IAS spectrum, 0-50x order.

Figure 4.53.: Generator harmonics in the IAS signal.
Figure 4.54.: The BPFI value in the IAS spectrum and in the Acceleration, four configurations.
Figure 4.55.: The BPFI value in the IAS spectrum and in the Acceleration, four configurations, zoom.
4.3.6. Power supply unbalance

A test is conducted in order to understand how a voltage unbalance is shown in the IAS measurement. The SANTERNO motor is decoupled from the Experimental Test Rig 3 and it is driven alone. The motor is in a wye-connected (Y or star) configuration. If the voltage sources have the same amplitude and frequency $\omega$ and are out of phase with each other by $120^\circ$, the voltages are said to be balanced, Fig. 4.56

$$V_{an} = V_{bn} = V_{cn} = V_{ab}/\sqrt{3} = V_{bc}/\sqrt{3} = V_{ca}/\sqrt{3}$$

(4.42)

A variable resistance ($0 - 24\Omega$) is installed between the electrical power grid and one motor phase. Three voltages are measured between each phase and the neutral. The values measured are reported in Table 4.13. The resistance at the motor mains generates three unbalanced voltages in the stator, because the neutral connector’s potential is not zero.

The IAS spectrum shows a variation in the orders 4.004x and 8.008x, Fig. 4.57 and Fig. 4.58. Its amplitude grows with the amount of electrical unbalance, Table 4.13. There is a small shift between the peaks due to the change of the slip value. The behaviour is related to the power supply frequency time harmonics:

$$f_r = 2k f \quad k = 1, 2$$

(4.43)

In this case:

$$f = 50Hz \quad f_r = 100Hz, 200Hz$$

(4.44)

<table>
<thead>
<tr>
<th>Test</th>
<th>$V_{cn}$</th>
<th>$V_{bn}$</th>
<th>$V_{an}$</th>
<th>Order 4.004x</th>
<th>Order 8.008x</th>
<th>Order 12.01x</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>233V</td>
<td>234V</td>
<td>234V</td>
<td>0.062 rad/s</td>
<td>0.018 rad/s</td>
<td>0.017 rad/s</td>
</tr>
<tr>
<td>2</td>
<td>231V</td>
<td>231V</td>
<td>234V</td>
<td>0.504 rad/s</td>
<td>0.023 rad/s</td>
<td>0.017 rad/s</td>
</tr>
<tr>
<td>3</td>
<td>226V</td>
<td>226V</td>
<td>237V</td>
<td>1.361 rad/s</td>
<td>0.037 rad/s</td>
<td>0.020 rad/s</td>
</tr>
<tr>
<td>4</td>
<td>223V</td>
<td>223V</td>
<td>238V</td>
<td>1.732 rad/s</td>
<td>0.041 rad/s</td>
<td>0.019 rad/s</td>
</tr>
</tbody>
</table>

Table 4.13.: RMS voltage measurements, phase-neutral

Figure 4.56.: Voltage balanced and unbalanced configuration
Figure 4.57.: Voltage unbalance measurement: IAS spectrum, 0-50x, b) zooming y axis
Figure 4.58.: Voltage unbalance measurement: IAS spectrum, order 4.004x (a), order 8.008x (b)
4.4. Measurements at Nidec ASI S.p.A.

4.4.1. CR 900 X4

A Nidec ASI CR 900 X4 machine (rating 14000kW, voltage 11000V) is tested under no load and load conditions measuring the Instantaneous Angular Speed, Fig. 4.59. The resistive torque is provided by a Zollner brake (a water pump). An inductive sensor and a phonic wheel are used to acquire the rotor speed, Fig. 4.60. There are 10 teeth, so at every revolution the sensor generates 10 pulses. A counter board NI measures the time elapsed (ET method) between the signal rising edges.

Fig. 4.62 shows the IAS for all the measurements. Note that in Fig. 4.62(a) there are 70000 shaft revolutions while in Fig. 4.62(b) there are 120000 cycles. This value corresponds to a data acquisition time of 4800 seconds. Fig. 4.62(a) shows an evolution: at the beginning the brake is not working properly due to a water leakage, then the system behaviour becomes stable. Considering 100 cycles, Fig. 4.63, the few number of teeth generate quite a sharp signal. In the loaded condition, the IAS has a bigger variation than in the case of no load.

A particular event occurred during the test: a bolt, holding the upper heat exchanger (Fig. 4.61), broke and the measured signal can be seen in the Fig. 4.64. This is a very interesting result considering the small inertia of the bolt in respect to the size of the motor.

The presence of the brake changes the shaft configuration and Fig. 4.65 shows the IAS spectrum before and after the installation. The slip effect is also shown. The linear scale and decibel scales present different information one in respect to the other: the former clearly displays the amplitudes, while the latter highlights the bottom part of the spectrum. Note that, after the coupling of the motor with the Zollner brake, the IAS spectrum shows peaks at new orders (Fig. 4.66). They are equal to the Fundamental Train Frequency of the bearings installed in the brake (6048MA), Table 4.14.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass Pass Frequency - Inner</td>
<td>BPFI</td>
</tr>
<tr>
<td>Bass Pass Frequency - Outer</td>
<td>BPFO</td>
</tr>
<tr>
<td>Fundamental Train Frequency (Cage)</td>
<td>FTF</td>
</tr>
<tr>
<td>Ball Spin Frequency (Rolling element)</td>
<td>BSF</td>
</tr>
</tbody>
</table>

Table 4.14.: Characteristic orders, bearing 6048MA

This test proved that:
- small data storage, it is possible to acquire hours of data a with few MB of storage;
- load changes are reported in a very clear and simple way, storing the machine’s history;
- 10 teeth allow the calculation of the IAS spectrum up to the order 5x.
- the FTF can be seen for the machine connected to the electric motor under test
Figure 4.59.: CR 900 X4, test loaded condition

Figure 4.60.: CR 900 X4, IAS sensor

Figure 4.61.: Bolt brakeage
Figure 4.62.: CR 900 X4: a) load; b) no load
Figure 4.63.: CR 900 X4: load no load conditions, 100 revolutions

Figure 4.64.: CR 900 X4, bolt brakeage
Figure 4.65.: CR 900 X4, IAS spectrum in load and no load conditions: a) decibel scale; b) linear scale
Figure 4.66.: CR 900 X4, 6048MA FTF frequency

Figure 4.67.: Motor CT 560 Y4
4.4.2. CT 560 Y4

The test is conducted on a Nidec ASI S.p.A. CT560 Y4 machine (rating 1900kW, voltage 3300V). The induction machine’s running speed is fixed at 500 rpm in a no load condition. The motor has an ELCIS EExd IIIC T5 encoder, with 1024 pulses per revolution, Fig. 4.67. In this case, an Analog approach is used to acquire the encoder signal with a LMS Pimento (50kS/s, 24-bit, ±5V, 300s) data acquisition system. The encoder is powered by an external device with a 20V supply voltage. The encoder output is a TTL signal (0-5V). The motor is driven by a power source with a fundamental frequency \( f = 17\)Hz.

Fig. 4.68 shows the signal acquired from the encoder output. A modulation related to the sampling frequency is present. The square wave has a frequency of:

\[
\frac{\text{Divisions} \times \text{rpm}}{60} = \frac{1024 \times 500}{60} = 8533.33 Hz \ll 50000Hz
\]  

(4.45)

A square wave can be reconstructed by an infinite number of sine waves. The combination of the sampling frequency and the square wave period generates the modulation, Fig. 4.69. The value of the modulation for 50kHz and 800kHz sampling frequency is calculated in Table 4.15. The modulation has a frequency of 1140Hz that corresponds at the order 140 in the IAS spectrum, Fig. 4.70. This measurement is not acceptable because the main peak is related to this modulation and the motor information is masked.

The signal is downsampled to 128ppr, Fig. 4.71(a). The result obtained does not show the modulation, Fig. 4.71(b). and the electromagnetic effect of the motor can be seen.

This test shows the limitation of the encoder’s square wave A/D acquisition. The use of an encoder with sinusoidal output is suggested with this analog method in order to acquire a sine wave with a frequency of 8533.33Hz. In this case there would not be modulation. In industry, the square wave output signal is very common, so the use of a counter board is recommended. Note that a 300s long signal, acquired at 50kHz has a 45MB size, while using a counter, the same signal is acquired with only 10MB.

\[
24\text{bit} = 3\text{Byte} \times 50kHz \times 300s = 45MB
\]  

(4.46)

\[
32\text{bit} = 4\text{Byte} \times 8533.33Hz \times 300s = 10MB
\]  

(4.47)

Figure 4.68.: The modulation in the signal acquired
Figure 4.69.: The source of the modulation at the order 140x: a) 50kHz; b) 800kHz

<table>
<thead>
<tr>
<th>Freq [Hz]</th>
<th>Order</th>
<th>Freq [Hz]</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1219.5</td>
<td>146.3415</td>
<td>2133.6</td>
<td>256.0273</td>
</tr>
<tr>
<td>1219.5</td>
<td>146.3415</td>
<td>2134.5</td>
<td>256.1366</td>
</tr>
</tbody>
</table>

Table 4.15.: The value of the modulation at 50kHz and 800kHz

Figure 4.70.: The IAS spectrum, 1024ppr
Figure 4.71.: Downsampling 128ppr: a) Calculated speed; b) IAS spectrum, 128ppr
5. Conclusion

This research proposes the measurement of the Instantaneous Angular Speed (IAS) as a condition monitoring tool for Induction Motors. The IAS is investigated and these guidelines can be recommended:

- care must be taken with the encoder installation from a mechanical and electrical point of view.
- the rotating disk should have a large diameter and built with the highest degree of accuracy possible.
- a geometrical error correction algorithm could be implemented and applied if necessary (phonic-wheel, zebra tape).
- an high speed counter should be used if the IAS measurement is analyzed in angular domain (combined with an encoder having more than 1024ppr), while a standard counter can be adopted when the order spectrum is considered.
- encoder decimation can be used when the machine’s behaviour does not require the visualization of high orders. For example, the 256ppr ETD method is perfectly able to satisfy this kind of electrical machine needs. Otherwise, an incremental encoder with 256ppr and ET counting method could be used. In these two cases, the maximum order is 128x and this is enough for the application due to the IAS measurement embedded filtering.
- the maximum machine order to analyze drives the choice of encoder divisions and counter frequency.
- IAS filtering could be considered as optional.
- IAS resolution could be chosen depending on the separation wanted between the peaks. The value suggested is from 128 to 4096 revolutions.
- a matrix approach could be applied in order to visualize motor behaviour from a statistical point of view, keeping the amount of stored data small.

The main advantages with respect to the vibration and the Motor Current Signature Analysis (MCSA) are the high resolution of the result obtained, combined with small data storage. The high quality information shows many high order harmonics that are not easy to interpret and correlate with the machine construction.

Rotor and stator excite magnetic flux density waves in the air gap. The slots, the distribution of windings in the slot, the input current waveform distribution, the air gap permeance fluctuation, the rotor eccentricity and the phase unbalance give rise to mechanical deformations and vibrations. Magnetomotive force (MMF) space harmonics, time harmonics, slot harmonics, eccentricity harmonics and saturation harmonics, produce parasitic higher harmonic forces and torques. In order to explain peaks found in the IAS spectrum, a review of the analytical formulas of electromagnetic fields generation in IM was carried out. Nevertheless, further work must be conducted in order to identify all the harmonics and sidebands present in the spectrum. From the experiments it is clear that the saturation harmonics are very strong in induction machines and they could contain interesting information.
From the experimental tests, the IAS has the potential of extracting this information:

- the Magneto Motive Force MMF space harmonics
- the rotor skewness
- the bearing Fundamental Train Frequency FTF
- the presence of a BPFI (inner race) bearing fault (without radial load)
- detection of the specific faulty bearing through its characteristic frequencies detection
- the load variation
- the power supply unbalance

The measurements at Nidec ASI S.p.A. confirmed these IAS capabilities.

In particular, the faulty bearing could be detected by IAS later than acceleration could, but in industry this information could be used as an end of life estimator: the bearing tested in ETR3 makes a lot of noise, but the motor is still running properly, so combining the IAS measurement with a temperature sensor (that is really the bearing’s end of life) could be an interesting industrial solution.

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A. Maintenance Terminology

Age Exploration (AE)  The process of determining the difference between perceived and intrinsic design life [55].

Condition-based Maintenance (CBM) or Condition Monitoring (CdM) is maintenance when need arises. This maintenance is performed after one or more indicators show that equipment is going to fail or that equipment performance is deteriorating. This concept is applicable to mission critical systems that incorporate active redundancy and fault reporting. It is also applicable to non-mission critical systems that lack redundancy and fault reporting. Condition-based maintenance was introduced to try to maintain the correct equipment at the right time. CBM is based on using real-time data to prioritize and optimize maintenance resources. A strong correlation exists between equipment age and failure rate. Individual component and equipment probability of failure can be determined statistically, and therefore components can be replaced or refurbished prior to failure. Condition-based Maintenance should not replace all interval based maintenance. Interval-based maintenance is still appropriate for those instances where an abrasive, erosive, or corrosive wear takes place; material properties change due to fatigue, embrittlement, or similar processes; or a clear correlation between age and functional reliability exists.

Continuous Monitoring One continuously monitors a critical piece of machinery by permanently mounting a number of transducers (usually temperature probes, proximeters, accelerometers, etc.) on the machine at the proper places. Each pickup is permanently wired to a panel meter in the control room. The panel meters have a set point with which to use the incoming signal to trigger a warning alarm. A higher set point at which either a higher level alarm goes off or the machine shuts down is also provided. Very often there will be some sort of voting logic in the decision to shut down. Although continuous systems are designed to look at every measured parameter during every second of machine operation, the data gathered is usually in an unrefined, unfiltered state. Thus, such a system will not tend to see incipient failures of low-energy mechanisms, such as bearings or couplings, until the failure is imminent. A periodic monitoring system using filtered vibration is required for advance notice of such problems. Because of the cost of mounting a great many sensors and wiring them into a control room, continuous monitoring tends to be quite expensive. The technique is therefore used sparingly. Continuous monitoring requires a great deal of expense and effort to set up in widely diverse areas of a plant. One of the major capital costs of setting up a continuous monitoring system lies in the cost of running cables. In the past, it has been necessary to run a cable from each transducer location to a control room for continuous monitoring. This cost had hampered the use and further development of continuous monitoring systems, except where absolutely necessary. Ethernet and wireless communication are now available and the cost of cabling has dropped.

Corrective Maintenance is a maintenance task performed to identify, isolate, and rectify a fault so that the failed equipment, machine, or system can be restored to an operational condition within the tolerances or limits established for in-service operations.
Diagnostics  One diagnoses a problem to get a clear understanding of its nature. In this way, optimal decisions as to the cure of the probable problem can be found. The art of properly diagnosing a problem usually requires an expert with a great deal of experience and the use of very sophisticated equipment.

Maintenance, Repair, and Operations - Overhaul (MRO)  All actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions.

Periodic Monitoring  Originally, this technique was used only in place of continuous monitoring for those machines where the cost of a continuous monitoring system was not justified. In this case, the watchman carried an overall velocity reading meter from machine to machine on a weekly or monthly basis. The levels at each bearing of each machine were written down in the hope of finding some incipient failure. One of the problems with this simple method of operation is that, while it is cost effective, some types of failure are unlikely to be predicted. Certain forcing mechanisms have high amplitudes of vibration at their forcing frequencies when they are operating normally, whereas other mechanisms do not exhibit significant levels until the instant of failure. For this reason, many modern periodic monitoring endeavors use filtered vibration readings to enhance the ability to predict incipient failure.

Planned Preventive Maintenance (PPM), Planned Maintenance (PM) or Scheduled Maintenance is any variety of scheduled maintenance to an object or item of equipment. Specifically, Planned Maintenance is a scheduled service visit carried out by a competent and suitable agent, to ensure that an item of equipment is operating correctly and to therefore avoid any unscheduled breakdown and downtime.

Precision Maintenance (PrM)  points at preserving the real standards of a machine. The key requirements for a precision maintenance program are: accurate fits and tolerance at operating temperature, Impeccably clean, contaminant-free lubricant life-long, distortion-free equipment for its entire life, rotating parts running true to centre, forces and loads into rigid mounts and supports, laser accurate alignment of shafts at operating temperature, high quality balancing of rotating parts, low total machine vibration, correct torques and tensions in all components, correct tools in the condition to do the task precisely, only in-specification parts installed, failure cause removal to increase reliability, proof-tests that precision is achieved, a business-wide system to apply the standards and requirements in a successful way [71, 74].

Predictive Testing & Inspection (PT&I) - Predictive Maintenance (PdM)  techniques are designed to help determine the condition of in-service equipment in order to predict when maintenance should be performed. This approach promises cost savings over routine or time-based preventive maintenance, because tasks are performed only when warranted. Predictive maintenance tends to include direct measurement of the item.

Preventive Maintenance  Preventive maintenance can be described as maintenance of equipment or systems before fault occurs. It can be divided into Planned Maintenance and Condition-Based Maintenance. The main difference of subgroups is determination of maintenance time, or determination of moment when maintenance should be performed. The only problem is in determining what age limit is necessary to assure reliable operation [36]. PM assumes that failure probabilities can be determined statistically for individual machines and components, and that replacing parts or performing adjustments in time can often preclude failure. For example, a common practice has been to replace or renew bearings after a specified number of operating hours, assuming that bearing failure rate increases with time in service. The introduction of computerized maintenance management systems and the availability of computers solved the problem of when (what age) to
overhaul many types of equipment in order to assure required reliability. Maintenance and operations, failure and reliability data being reported by airlines highlighted problems with this approach. Over the years, however, it was found that many types of failures could not be prevented no matter how intensive the maintenance activities.

**Proactive Maintenance** can be either a predictive or preventive task intended to intervene before a failure can occur.

**Reactive Maintenance** is a task that is performed after failure occurred or a defect has developed, intended to eliminate the defect and repair resulting damage.

**Reliability Centered Maintenance (RCM)** The fundamental goals of Reliability-Centered Maintenance is to maintain system functionality by ensuring all maintenance actions were designed to maximize system reliability at minimum cost. To accomplish this, the RCM process is a structured approach that requires the analyst to justify maintenance requirements by answering a series of questions.

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?
- What functions does the system perform?
- What functional failures might occur?
- Which of the functional failures are likely to occur?
- Are the functional failures evident to the operating crew?
- What are the consequences of failure on safety, mission, and cost?
- What is the relative risk of failure in terms of probability of failure and severity of failure?
- What, if anything, can be done to prevent likely failures?
- What is the cost of trying to prevent failures?

The RCM methodology guides us to make maintenance strategy choices using the four equipment operating decisions to do run-to-failure when consequences permit, to do preventive maintenance and replace aged parts, to do predictive maintenance and look for parts’ failure initiation, or to redesign the equipment to remove failure causes (today we have an additional, better strategy Precision Maintenance). RCM replaces time based maintenance with on-condition maintenance wherever possible. RCM should produce the perfect maintenance program: the least maintenance costs for low operational risk and high equipment reliability. In operating equipment the P-F time window is not stable and certain. For parts that wear from use or age there is a high chance that we can judge their degradation rate and wait until nearer the F point to do maintenance. But for parts that fail randomly during operation from operation-induced stresses we must immediately reduce the stress levels and start planning for rectification. But miss the P point or wait too long to rectify the problem and you end up in reactive behaviour. But RCM requires complete compliance to an inflexible maintenance schedule in order to find the P point of the degradation curve. Once the P point is found RCM demands that
stress levels in the item be reduced to sure safe values until rectification is completed. RCM also requires sure delivery of a specified level of task quality when doing maintenance work so equipment is returned to a known condition that produces a known minimum service life. Simply by using the RCM methodology to select maintenance strategy does not imbed the RCM discipline and practices needed to get the benefits that RCM promises.

In the bibliography there are many books about RCM theory [55, 56, 53, 31, 57, 73], RCM statistics [51, 72] and how to build RCM programs [14, 22, 70].

**Total Productive Maintenance (TPM)** [52] One of the main objectives of TPM is to increase the productivity of plant and equipment with a modest investment in maintenance Total Quality management (TQM) and Total Productive Maintenance (TPM) are considered as the key operational activities of the quality management system. In order for TPM to be effective, the full support of the total workforce is required. This should result in accomplishing the goal of TPM: "Enhance the volume of the production, employee morale and job satisfaction” [61].

**Trending** Although the simple comparison of currently gathered filtered vibration data to a predetermined baseline will generally indicate a problem in a machine, the ability to estimate how much longer the machine may be allowed to run before repair requires a long-term trend of the machine’s condition with time. For example, a comparison of the vibration levels of two different bearings, with about the same baseline level and current level, will show that bearing A is slowly deteriorating while bearing B is about to self-destruct.

**Untrendable Failures** An untrendable failure progresses from its initiation as a barely detectable fault to a complete failure in a time period that is shorter than the periodic monitoring time interval assigned to the machine.
B. Nidec ASI S.p.A

Nidec started out as the dream of its CEO Shigenobu Nagamori and his three partners back in 1973. From the beginning their goal was to become number one in electric drive solutions, with a strong focus on electric motors. Over the years, through hard work and determination, the company has grown, expanding from its original product base of motors for Information & Communication Technologies into motors for home appliances, automobiles, office equipment and industrial machinery.

With a work force of approximately 98,000 and operations in more than 18 countries, Nidec is well positioned to become the number one brand in electric drive solutions worldwide. Quoted on the New York Stock Exchange (NYSE) since 2001, Nidec is headquartered in Kyoto, Japan.

The core business: Energy, Marine, Metals, Oil & Gas and General Industry (cement, water treatment, rubber and plastic, materials handling, glass, ceramics, paper and ropeway).

Nidec acquired Ansaldo Sistemi Industriali S.p.A. (Monfalcone, Italy) on April 11, 2012 from HVEASI Holding, B.V. (Netherlands). Information on ASI:

1. Company Name: Ansaldo Sistemi Industriali S.p.A.
2. Headquarters: Milan, Italy
3. Year of Establishment: 1853
4. Principal Places of Business: Italy (Milan, Monfalcone, Montebello and Genoa), France (Roche-La-Moliere), and Russia (Moscow)
5. Principal Businesses:
   - Motors, Generators and Drives Business
   - Industrial Systems and Automation Business
   - Services (Maintenance) Business
6. Employees: 1,217
7. Sales in Fiscal Year 2011: 292.0 million (unaudited)
8. Assets as of December 31, 2011 (unaudited):
   - Current Assets: 469.1 million
   - Fixed Assets: 56.0 million

Nidec ASI is one of the world’s leading suppliers of the complete electrical package which includes electric power and control systems, electric motors and generators, LV and MV drives and a precise Power Supply and Power Quality components. Each solution is tailored to client life cycle requirements and guarantees performance, reliability and safety.

Nidec ASI (Monfalcone plant) offers a wide range of engineered-to-order electric motors and generators to meet customers demanding specifications, such as (Fig. B.1):

- AC Induction Machines
- Synchronous Machines
- DC Machines
- Permanent Magnet Machines
- Explosion Proof Machines

The induction machines are built with an aluminium squirrel cage rotor. The electric motors and generators share many common features to guarantee their robust design for example: rotor packs are made from single punch laminations up to size 1000, stators are built as self contained units which are mounted into the frame after the coils have been inserted and the whole unit has undergone our MICASYSTEMÂ VPI process. AC synchronous machines are the preferred choice on large compressor and vertical pump applications. They are also widely used for wind tunnel fans and cycloconverter applications. Nidec ASI has consolidated experience in generators coupled to diesel engines and turbines of all types. These generators are specifically designed with all the construction features to withstand the pulsating torque generated by a diesel engine to ensure smooth parallel operation.

Nidec ASI is the expert in special application machines. Based on a modular design, the Nidec ASI DC machines offers a vast selection of mounting arrangements, cooling systems, types of protection and accessories to choose from in order to guarantee maximum flexibility in meeting specific application needs. Nidec ASI has a new series of permanent magnet machines specifically designed for wind power plants, biomass, hydro-electric and coupled to high speed compressors for air treatment plants. This series covers a wide speed range, from very low speed solutions up to high speed ones, with power ratings from 100 kW up to 5 MW. These electric machines can be supplied with traditional or magnetic bearings for oil-free solutions. For hazardous areas, Nidec ASI offers two special machines: Series ET and series CAD. Series ET is the ideal solution for Ex d areas and is certified for Group IIB + H2 classified areas. Series CAD is ideal for installation in hazardous areas where Ex d IIB T3/T4 (IEC standards) protection is required. Their external cooling fins and internal fans, streamline air flow for optimum cooling. This optimized cooling system and the special electromagnetic design that went into making this series also make series CAD suitable for variable speed drive applications. Further information can be found at http://www.nidec-asi.com/
C. Incremental Encoder

The encoder is an electro-mechanic device, converting angular position of its shaft into a digital electric signal. When connected to suitable electronic circuits and through proper mechanical link, the encoder is able to measure angular displacements, linear and circular movements and also rotational speed and accelerations. A collimated light beam is aimed against two radial reticles: a static and a moving reticle (disc). Light that can pass through both reticles drops on a group of phototransistors placed immediately beyond the static reticle. By using several slots (instead of only one) on both reticles, the resulting electric signal is rather strong and actually is the average of many lines of the rotating disc. In this manner, the electric output is not so sensitive to small disc imperfections or to small spurious parts in the optic system.
For that reason, incremental encoders yield a smaller "jitter". Encoder performance is further enhanced by the push-pull method used in the scanning assembly. This system, in fact, compares the output signal of two phototransistors, one of them being in the lit area while the other is in the dark area, thus obtaining very stable output signals, even under variations of power supply voltage or ambient temperature.
Gallium arsenide light source (LED) warrants a long operating life (100000 hours), while the filament lamp life is rather short (5000 to 40000 hours). Precision and quality of the encoder are in fact directly proportional to the disc quality. The disc is made of crystal or plastic.
The disc of an incremental encoder is marked with a series of uniform lines in a single track around the perimeter. As the lines interrupt the light beam, "increments" of information are produced in the form of a square wave pulse train output signal. The frequency of the pulses relates to the number of lines on the disc and the disc speed. The amplitude of the pulses relates to the excitation supply.
The basic signal "A" provides information on single direction rotational movement. By using two scanning heads it is possible to produce a second wave train "B" with 90° displacement and thus sensing direction of rotation and allowing up/down count of angular or linear displacements. A single line can be placed on the disc to provide a marker pulse "C" for reference purposes. Incremental encoder, differently from absolute, does not keep the information when shut down, but has the advantage of a lower price and, due to its wide range of resolutions and high operating frequency, offers a broad field of applications.
Ball bearings used on shaft encoders are of high importance, as the quality of encoders also relies on the coupling precision of their mechanic parts. High precision ball bearings (ABEC 5-7) are necessary. Load on the encoder shaft and consequently on its ball bearings affects mechanical life of the transducer. Use of rigid couplings, axially and/or radially, will directly transfer all backlash and misalignment of the system on the ball bearings and will drastically reduce encoder life. It is therefore absolutely necessary that coupling between encoder shaft and driving shaft is made through a joint, showing some elasticity in axial and radial sense and being stiff in torsional sense.
The encoder operating frequency affects the connecting distance to the counting electronic board in an inversely proportional way, that is, the higher the frequency, the higher the signal attenuation (due to parasitic capacity of the cable, that increases with cable length). To avoid these problems, several output electronics should be considered (open collector, push-pull, line driver, a.s.o.) to fit with various line lengths. Furthermore, properly designed cables are necessary for a proper, matched connection between encoder and electronic equipment. A shield equipped cable is mandatory and joints should be avoided. The cable line must be far enough from other power electronic cables (solenoids, relays, pumps).
The TEKEL TSW80P incremental encoder has a stainless steel hollow shaft fixed rigidly at the motor shaft through a ring. The body is made of aluminium and the case in Polyamide 6. The speed range is up to 3000rpm and the useful bearing life is $5 \times 10^9$ cycles (6 years 24/7 at 1500rpm). The maximum output frequency is 200kHz. An Index signal is provided. The encoder’s code is L.1024 S.K1.15PL40.LD2 - 528.X710X.300: 1024ppr, LINE DRIVER-PUSH PULL, supply 5-28V, output 5-28V. There is a MIL connector 10 pins MS3102A 18-1P, TYPE "C", wiring S10-L10, Fig. C.1.

Supply $V_{cc} = 5V$, ”Low” $V_{low} \leq 0.5V$, ”Hi” $V_{hi} = V_{cc} - 2V$, Fig. C.2

**Figure C.1.: MIL MS3102A 18-1P, TYPE "C"**

**Figure C.2.: Wiring LD2**
D. IaSaT - Instantaneous Angular Speed Analysis Tool

A MATLAB tool, called IaSaT - Instantaneous Angular Speed Analysis Tool, is developed to analyze motor behaviour and create the figures in this thesis. The software is able to:

- load a pre-processed figure or a measurement file
- calculate the FFT spectrum, with the possibility of setting the main parameters
- plot harmonics
- plot sidebands
- plot bearing’s characteristic frequencies
- plot Induction Motor characteristic frequencies
- save the figure

Figure D.1.: IaSaT, raw signal
Figure D.2.: IaSaT, FFT processing

Figure D.3.: IaSaT, Induction Motor frequency analysis
References


