Chapter 1 Problem statement and literature survey

1.1 Introduction

The order tracking technique is one of the important and effective vibration analysis techniques for rotating machinery. The advantages of order tracking over other vibration techniques mainly lie in analysing non-stationary noise and vibration signals which vary in frequency with the rotation of a reference shaft or shafts. The analysis of non-stationary conditions requires additional information, as compared to steady state conditions, for accurate results to be obtained. Normally the additional information is provided in the form of a tachometer signal measured on a reference shaft or shafts of the machine.

Order domain analysis relates the vibration signal to the rotational speed of the shaft, instead of an absolute frequency base. In this way, vibration components that are proportional to multiples of the running speed can easily be identified. In the early stages, order tracking was performed by sampling the analog vibration signal at constant shaft increments, directly with the help of an analog instrument. However due to the high cost and complexity of the equipment, this kind of method is being used less and less. The mainstay of modern order tracking is post-process order tracking. It entails measuring the vibration signal and additional rotational speed information (usually a tachometer signal) simultaneously and processing the data after the measurement, which makes the whole process more economical and flexible. In the literature, many different order tracking techniques which rely on post-processing order tracking, are described. Some of these are frequently discussed and researched in the context of condition monitoring of machinery. Each technique has its own advantages and disadvantages. However nearly all of them have unique advantages in their own right and therefore it is worthwhile to study these techniques intensively.

Firstly, the simplest and most commonly used method is Fourier Transform based Order Tracking (FT-OT). This is a widely used method however it suffers from the limitations of Fourier analysis (Blough, 2003). Secondly, another frequently used and extensively researched technique is angle domain sampling based order tracking (AD-OT) or computed order tracking (COT). It re-samples uniform time domain data into the angle domain and therefore overcomes the limitation of non-stationarity due to the variation in rotational speed. But the process of re-sampling brings unavoidable assumptions and constraints (Fyfe and Munck, 1997) which compromise the ability of this kind of order tracking technique. Thirdly, a recent waveform reconstruction based method is Vold-Kalman filter order tracking (VKF-OT). (The term 'waveform reconstruction' used in the context of order tracking analysis was first introduced by Pan, Liao and Chiu, 2007). It is a technique that extracts time domain order information from the raw data and features unique advantages in overcoming many of the limitations of other order tracking techniques, such as allowing high-performance tracking of harmonic responses or orders and allowing beat free extraction of close and crossing orders, etc. (Brüel and Kjær, 2007). Similarly, another well known waveform reconstruction order tracking technique is Gabor order tracking proposed by Albright and Qian (2001). This is a technique that claims to be more intuitive, more powerful and can be used when rotational speed is not available. Although these two techniques have excellent abilities of extracting order signals in the time domain, neither of them however can get rid of the non-stationary effects in the extracted or filtered time domain signals due to the variation of rotational speed, and therefore pose difficulties for further analysis of the time domain signals by conventional signal processing techniques such as Fourier analysis. Lastly, a useful technique that deals with non-stationary and nonlinear signals and which was not specifically developed for order tracking may also be treated as a special waveform reconstruction order tracking technique. This is the intrinsic mode function (IMF) from empirical mode decomposition (EMD). In recent years, many researchers have done a great deal of research by using this technique to monitor rotating machinery conditions and have proven it to be effective. This will be extensively investigated in the following. However, the relationship between an order and an IMF from the EMD method for rotating machinery vibrations and the fact that it can indeed capture order information from rotating machinery vibration data has not been analysed in the literature.

Besides, there are still some other order tracking techniques, such as time variant discrete Fourier transform order tracking (TVDFT), the maximum likelihood process and the Prony residue estimation process, as well as methods based on conventional digital filtering (Blough, 2003). Yet these techniques have not attracted much interest in condition monitoring, compared to the order tracking methods mentioned above. In fact, they usually suffer from various constraints which discourage their application. For example, Blough (2003) mentions that the Prony residue estimation process has several disadvantages in its computational complexity and the requirement that a model order of the data must be known. Determination of the model order, or number of orders and resonances in the data, is not trivial, because it is typically a function of rotational speed and the resonances which are excited at certain instant in time. He further mentions that order tracking methods that are based on conventional digital filtering all appear inferior to the Vold/Vold–Kalman filtering methods because of their pass band shapes. These filtering methods also tend to be computationally demanding.

In general, each order tracking technique has its own advantages and disadvantages. It is not easy to conclude that one method is absolutely superior to the others, since they all have benefits for different applications. However, in terms of real application of signal processing in vibration monitoring of rotating machines, those more widely available and proven effective order tracking methods deserve intensive emphasis for investigating order and related vibration signals.

From a vibration monitoring point of view, order signals as well as an understanding of these orders and its related vibration signals are of great importance for monitoring rotating machine conditions. Fortunately, with the development of computer capabilities in recent years, researchers can now more easily work on the application of different order tracking techniques in monitoring of rotating machines. General speaking, most of the research described in the literature focus on the interpretation of the theory of each order tracking technique and the application of techniques in simulation models or real machinery environments. Examples of this are Potter (1990), Fyfe and Munck (1997), Huang et al. (1998), Gade et al., (1999), Blough (2003), Brandt et al. (2005), Pan and Lin (2006) and Feldman (2008, 2009), etc.. In practical applications, various companies have commercialized order tracking methods in their signal analyzers, such as, PULSE which is supplied by Brüel and Kjær, the Rotate software supplied by ATA Engineering, Vibratools from Matlab, The Dewetron, LMS international, Benstone Instruments (Fieldpaq2+1 channel dynamic signal analyzer), Lambda photometics (SR785 dynamic signal analyzer), Xi'an space star technology (SS-DY dynamic signal analyzer), OROS, etc.. One can easily find all kinds of signal analyzers which include either COT, VKF-OT or both. However the ideal of using these techniques together has not been reported. The improvement of order tracking analysis capability through the use of different order tracking techniques for diagnosing machine faults, has not yet attracted intensive research in the field. Thus, it is clear that order tracking techniques have been intensively studied in their theories and widely implemented in real practice on their own, however combining different order tracking methods and exploiting abilities in machine fault diagnostics are few reported and deserve further researches. It is, therefore proposed in this research that significant added value may be obtained in order tracking research by exploiting the distinct characteristics of different order tracking techniques and combining them into enhanced diagnostic tools for rotating machinery diagnosis.

Thus, in this research, three widely researched order tracking techniques are studied and developed into improved techniques that combine the abilities of different order tracking methods to achieve augmented order tracking for rotating machine diagnostics.

In the following, firstly, the strengths and weaknesses of different traditional order tracking methods in condition monitoring are discussed. Based upon these discussions, directions into which order tracking techniques for condition monitoring may be improved, are proposed. The research will then use three widely available order tracking techniques to exploit these avenues to develop improved techniques.

1.2 Towards the improvement of order tracking analysis

It is not surprising to find that in the literature each order tracking technique has been studied and developed extensively in its own right. However, it may be hypothesised that through combining different order tracking techniques together, instead of focusing on each individual method alone, one may also bring about several useful advantages in the order tracking field of study. This would however require a systematic understanding of which would be the most appropriate order tracking techniques and how to combine them in order to extract maximal benefit.

In the literature order tracking techniques are classified into two categories, namely, waveform reconstruction and non-reconstruction schemes (Pan, Liao and Chiu, 2007). Vold-Kalman filter order tracking is a typical example of a waveform reconstruction scheme. The distinct characteristic of this scheme is that it finally yields time domain order waveforms without intentionally transforming signals. The waveform non-reconstruction scheme, however, will not lead to time domain data, such as computed order tracking where the time domain signals are re-sampled in the angle domain, using various kinds of interpolation methods. Different kinds of order tracking methods may be developed, but they are basically being classified in one of the schemes mentioned above.

To improve order tracking analysis, one should therefore investigate both schemes of methods. For implementation in this research, it is therefore essential to consider typical and widely used order tracking methods from both schemes. Thus, computed order tracking (a waveform non-reconstruction scheme), Vold-Kalman filter order tracking (a waveform reconstruction scheme) and intrinsic mode function from empirical mode decomposition (another waveform reconstruction scheme) are emphasized and studied. In this context the intrinsic mode function from empirical mode decomposition is also treated as a special kind of order tracking method. Its unique characteristics in terms of order signals will be explored in chapter 2. In the following, some aspects regarding the strengths and weaknesses of the selected techniques are discussed so that directions for possible improvements in the order tracking may be clarified. The inter-relationship between the three independent order tracking techniques is also explained in the following scope of work, so that the reader may understand how this work integrates these three order tracking methods.

1.2.1 Computed order tracking

To begin with, the strengths and weaknesses of computed order tracking (COT) are first investigated. Important background to COT is given by authors such as Potter (1990) and Fyfe and Munck (1997). Except for the detailed studies of the

COT technique itself in these papers, such as different interpolation methods, influence factors of accuracy, etc., some advantages of the method in terms of condition monitoring are discussed in the following.

Firstly, the idea of the technique is essentially to simplify the application of Fourier analysis, since the kernels of Fourier analysis are constant frequency (Blough, 2003). Whatever procedures are used for re-sampling of the data by COT, the final Fourier analysis is intended to yield clear figures through the transformation of signals where frequency variations in speed has been excluded. Fourier analysis is a very common signal processing method and this makes the COT technique easier to access and understand. Secondly, COT has been proved very useful in real practice (such as Eggers, Heyns and Stander, 2007) and also been commercialized into software in several vibration monitoring tool packages (such as Matlab). Thirdly, COT analysis may provide a clear picture of the raw signal in terms of rotational speed. This is a very useful perspective for an analyst to understand rotating machine vibrations. Nowadays, COT is one of the important mainstream order tracking methods and a well established technique.

Apart from these key advantages of the technique, some limitations should also be pointed out. Firstly, the COT method is normally set to deal with signals where several rotational speed harmonic vibrations may coexist, therefore usually the final spectrum map will yield several order components. This may lead to some non-dominant order signals easily being neglected and analysts have to accept this inconvenience throughout the analysis process. The shortcoming of the inability to focus on each individual order signal, sometimes limits the application of COT. Secondly, since the whole re-sampling process is strictly based upon rotational speed signals, those signals that are not strictly related to rotational speed information will be naturally de-emphasized, such as response at the natural frequencies of the system. This may lead to a loss of some important system information in the order domain. Thirdly, its unavoidable assumptions and different interpolation errors will, of course, influence the accuracy of the results. Besides, for COT, rotational speed information is crucial for its calculation. In the absence of rotational speed information, the COT method is no longer applicable.

From the above it may be surmised that while the COT technique is a very practical and useful order tracking method, if breakthroughs could be made with respect to these limitations, it could definitely enhance the technique.

1.2.2 Vold-Kalman filter order tracking

For Vold-Kalman filter order tracking (VKF-OT), the following papers are key to understanding the technique: Herlufsen et al. (1999), Blough (2003), Tůma (2005), as well as Pan and Lin (2006). The above-mentioned papers give detailed accounts of its theory and applications. Here we point out some of the advantages and limitations associated with VKF-OT. Firstly, VKF-OT does not involve the assumptions and interpolations as are done in COT and may therefore achieve more accurate results. This is because of the use of a concise mathematical adaptive filter instead of re-sampling signals. This leads to VKF-OT having several advantages over other order tracking methods. This will be further discussed in the following VKF-OT literature survey. Secondly, the use of an adaptive filter also leads to the order signals remaining in the familiar time domain and allows focusing on the order of interest, excluding the influences from other signals. Figurative speaking, the technique provides a pair of spectacles to specifically see certain information of interest. These characteristics make VKF-OT unique and very useful in the field of order tracking.

On the other hand, the limitations of the technique are also obvious. First of all, again due to the use of the adaptive filter, the signal variation, such as frequency variation caused by rotational speed, still remains in the filtered order signal. This, of course, influences Fourier analysis of the filtered time domain signal. Secondly, the technique is not easy to grasp for an inexperienced analyst, and it usually takes time to become familiar with the technique. This is also pointed out in some papers (such as Blough, 2003). Thirdly, the advantage of filtering specific orders from raw signals may also become a disadvantage in terms of condition monitoring, since it may easily lose vibration signals that modulate orders of interest, which usually contain useful machine condition information.

In short, VKF-OT may offer more advantages compared to other order tracking methods in order extraction. Through its strict mathematical adaptive filter, orders of interest can be specifically focused on for examination. However, its adaptive nature also brings disadvantages with respect to Fourier analysis and its difficulty in grasping sometimes becomes a barrier for its advancement in practical applications.

1.2.3 Intrinsic mode functions through empirical mode decomposition

Decomposition of intrinsic mode functions (IMF) through the empirical mode decomposition (EMD) method is also discussed in this research, as a special kind of order tracking method. The main reason why it may be considered as a special kind of order tracking analysis, can be ascribed to its empirical adaptive nature to decompose signals. Researchers such as Flandrin, Rilling and Gonçalvés (2004) conclude that the EMD process act more like a group of narrow band filters, and the method can be treated as a self-adaptive dyadic filter bank. Once one understands VKF-OT and IMFs from EMD in theory, it becomes easy to find connections between IMFs and VKF-OT results. Both of the two methods use adaptive filters to extract time domain signals. The difference is that one is a strictly mathematically defined filter (VKF-OT) while the other is empirical (EMD). Consequently, we may treat an IMF from EMD as a special kind of order tracking for rotating machine vibration signals. For details of the relationship between an order and an IMF, the reader may refer to chapter 2.

However, the question remains as to the advantages and limitations for this special kind of order tracking analysis for the analysis of vibrations in the context of condition monitoring. As indicated by the word ‘empirical’ in the name, the IMF is based upon the signal itself and in the process of empirical mode decomposition to obtain IMFs, no additional information is needed, such as machine speed information, therefore it is not limited to the case where rotational speed must be available. This is totally different form COT and VKF-OT. Most importantly, the advantage of this empirical nature is very useful for fault diagnosis of rotating machines. Machine fault related vibrations are synchronous or non-synchronous with rotational speed. These vibration signals modulate regular order signals. They are usually unpredictable, and the empirical nature of the EMD method helps the analyst to capture all kinds of these possible vibrations together with the orders of interest. It should also be borne in mind that, for rotating machines, order signals will usually dominate the vibration response. And IMFs are very well suited to include both order signals and other vibrations that could possibly modulate them. The EMD process therefore decomposes the rotating machine vibration signals in the form of different IMFs, through which orders and vibrations that modulate them are packaged together and distributed into different IMFs. This effect is not possible to achieve by using any other traditional order tracking methods. Thus, it is worthwhile investigating the abilities of IMF in terms of orders for condition monitoring. Furthermore, though the process of decomposing IMFs through EMD is not guided through a strict mathematical filter, the procedures of EMD however also enforce the distinct nature of the signal structure.

Huang et al. (1998) state that an abstract intrinsic mode function (IMF) as a signal satisfies two conditions:

- In the whole signal segment, the number of extrema and the number of zero crossings must be either equal or differ at most by one.
- At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

From this original definition of IMF it is easy to infer that each IMF is a symmetric and zero mean natured oscillation wave. This excludes two or more peaks within two successive zero crossings. (Huang et al., 1998) The simple structure of an IMF may also bring advantages for the analysis process. This characteristic is used in the current research and discussed in detail in Chapter 2. Lastly, another important advantage of IMFs is the absence of the need for rotational speed information during the EMD process. This makes this technique more accessible and practical in real application.

However from another perspective, the above mentioned advantages of IMFs may also become its limitations. The empirical nature and the absence of rotational speed information imply that more than one mode of oscillating signals can be included in one IMF. Therefore in practice it is usually not easy to extract single order signals alone through an IMF. Though ideally, an IMF is to extract one oscillation mode and therefore a single order signal is supposed to be extracted, the resolution of IMF however limits its ability to focus on a single order signal alone, especially when different vibrations are entwined together. The resolution obtainable through IMF is further studied in Chapter 2, paragraph 2.2.3.

This is an obvious disadvantage compared with VKF-OT. However, this technique actually enriches the content of order signals for condition monitoring purposes and deserves more in-depth research in the context of order analysis.

1.2.4 Improved order tracking

The discussions in the previous paragraph have pointed out some of the important pros and cons of different order tracking techniques. This points towards a number of possible improvements of order tracking techniques which should be researched. Advantages could be further developed and limitations may be avoided where applicable. Naturally not all the advantages and limitations of these techniques will be addressed. Intelligent use of different characteristics of these techniques should be introduced to exploit the advantages and avoid the limitations for condition monitoring purposes. Through studies of the above order tracking techniques, three aspects are identified and highlighted for the integration of three independent order tracking methods, namely:

1. Whether rotational speed information is required or not,
2. Whether order signals can be extracted for study, and
3. Whether the effect of speed variation can be handled.

As a result, improved approaches are therefore developed. This is summarised in Table 1.1.

Table 1.1 Approaches to improving order tracking methods

	Order tracking method	Need for rotational speed info (√/×)	An order can be extracted for study (√/×)	Speed variation effects can be handled (√/×)	
	COT	√	×	√	VKF/COT
IMF/COT	VKF-OT	√	√	×	IMF/VKF
	IMF	×	√*	×	

* For an IMF, an order signal can be extracted, but the whole signal comprises the order signal plus other possible vibrations that modulate the order.

Based upon the previous discussions and Table 1.1, three approaches to the improvement of order tracking are proposed here:

VKF/COT:

Combining the advantage of VKF-OT in its ability to focus on individual orders and the advantage of COT to get rid of speed variation effects, a sequentially combined application of Vold-Kalman filtering and computed order tracking (VKC–OT) may be developed. The shortcoming of possible non-stationarity, due to the rotational speed in VKF-OT is overcome by COT. And the shortcoming of COT with its inability to focus on each individual order, is compensated for by VKF-OT. The combination of these two techniques enhances the ability of condition monitoring by complementary use of two traditional order tracking methods. The usefulness of this improved order tracking technique mainly lies in the ability to obtain a clear and focused order component which can be tracked.

IMF/VKF:

Here we take advantage of the fact that an IMF may include order signals plus other possible vibrations that modulate the orders, as well as the VKF-OT advantage to strictly focus on order signals. Subtracting order focused VKF-OT results from an IMF, order signals and other possible vibrations that modulate orders can be separated and therefore an IMF can be further decomposed in terms of rotational speed. In this way one may extract useful machine condition information which is intractable by application of EMD or VKF-OT in isolation alone. Therefore, an intrinsic mode function and Vold-Kalman filter order tracking method (IVK-OT) is developed to further decompose an IMF. This may render useful machine fault information for condition monitoring.

IMF/COT:

Taking advantage of the simple data structure of an IMF and the lack of required rotational speed information, while at the same time borrowing re-sampling ideas from COT to get rid of speed varying effects, an intrinsic cycle re-sampling (ICR) method is developed, so that an approximation of computed order tracking effects is possible, without the need for rotational speed. In this approach, COT is not directly used together with the intrinsic mode function, but the re-sampling idea is borrowed from COT and applied onto an IMF. This leads to a practical alternative method for condition monitoring.

Three new approaches to improved order tracking are therefore proposed. They are the main contributions of this work. They will be further explained and discussed in detail in chapter 2 to clarify how these techniques are being combined. Their usefulness as well as effectiveness in condition monitoring is subsequently demonstrated in Chapters 3 and 4 through simulation and experimental studies. But before that, a comprehensive literature survey of the three basic order tracking techniques is conducted. After that, the inter-relationship between COT, VKF-OT and IMF from EMD will be discussed in the scope of work, so as to elucidate of how this work integrates these ideas.

1.3 A review of three basic order tracking methods

1.3.1 Computed order tracking

Computed order tracking (COT) can also be called angle domain sampling based order tracking (AD-OT). This technique was originally published by Potter and his colleagues from Hewlett Packard in 1989 (Potter, 1990). However Hewlett Packard considers the exact implementation of the technique to be proprietary, and as such has not published many of the details. It has been more than 20 years since this method was first introduced, and some papers discussing the theory and implementation of this specific technique have become widely available. In discussing COT, the most important part is to understand the re-sampling process. In the context of this work this is particularly important since the intrinsic cycle re-sampling (ICR) technique which will be introduced later will use some of the ideas from the re-sampling process. Therefore, in the following, the re-sampling process will be discussed in detail and the current research in COT will be surveyed thereafter.

a. The re-sampling process

Basically, COT requires sampling of the vibration signal at constant angular increments of the shaft and hence at a rate proportional to the shaft speed. Therefore, the core of the re-sampling process is to capture the relationship between the time and rotational angle based upon shaft speed. However, if the variation of shaft speed is involved in the relationship, then consideration of the acceleration of the shaft is unavoidable. The assumption is usually made that the shaft angular acceleration is constant. With regard to this point, a study of the paper by Fyfe and Munck (1997) gives a simple and precise mathematical explanation which is crucial for understanding the re-sampling process. In their research, a constant angular acceleration is assumed and the shaft angle θ is described by a quadratic equation of the following form:

$$\theta(t) = b_0 + b_1 t + b_2 t^2 \tag{1.1}$$

The unknown coefficients b_0, b_1 and b_2 are found by fitting three successive keyphasor arrival times t_1, t_2 and t_3 which occur at known shaft angle increments. Once these values are known, equation (1.1) may be solved for t, yielding

$$t = \left(\frac{1}{2b_2} \left[\sqrt{4b_2(\theta - b_0) + b_1^2} - b_1 \right] \right) \tag{1.2}$$

From this equation, any value of θ may be entered and the corresponding time t will be returned. This forms the basis of the re-sampling algorithm.

Based upon the above explanation of re-sampling, one should discuss some of the key assumptions. Obviously, since the assumption of constant angular acceleration, $\ddot{\theta}(t) = 2b_2$ the above calculation is not an ideal solution for the re-sampling problem. For the real machine start-up or coast down, the angular acceleration may generally not be constant. Therefore the angular velocity may not be linear. Figure 1.1 illustrates an exaggerated case: the continuous line is a possible real angular speed time history, while the dashed straight line may be used in COT analysis under the assumption of constant angular acceleration.

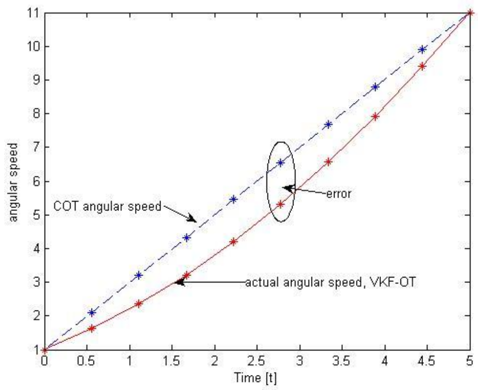


Figure 1.1 Possible real angular speed time history and the COT assumption

From Figure 1.1, the angular speed error introduced by the assumption is clear. In some software (such as: Vibratools in Matlab, 2005), this is even further simplified by assuming zero angular acceleration for one revolution, with a corresponding constant angular velocity. This is of course not an ideal choice, especially when rotational speed is slow and ever changing as is the case shown in Figure 1.1. However it becomes a comparatively better choice when one considers high speed rotating machines with small angular acceleration. For normal machinery, a sharp acceleration start-up or coast down is not desirable for the sake of machine life, and hence the shaft acceleration is usually small. Thus, the assumption of zero angular acceleration within one revolution becomes a reasonable choice. In the following chapters, this assumption will be used as a basis of COT analysis. However the limitations of this assumption should always be borne in mind.

For example: once the zero acceleration assumption is applied, how does the sampling within each revolution influence the final result? Consider for instance the case of 100 samples per revolution, which means that over the period of one sample the angular displacement is $\theta = 360^{\circ}/100 = 3.6^{\circ}$. However, if 10 samples per revolution are taken, the angular displacement between each sample becomes $\theta = 360^{\circ}/10 = 36^{\circ}$. Clearly, the incremental difference here is very large between the different choices of sampling increments. If 100 and 10 samples are used to sample a basic sinusoidal wave over 5 seconds, the results are shown in Figure 1.2.

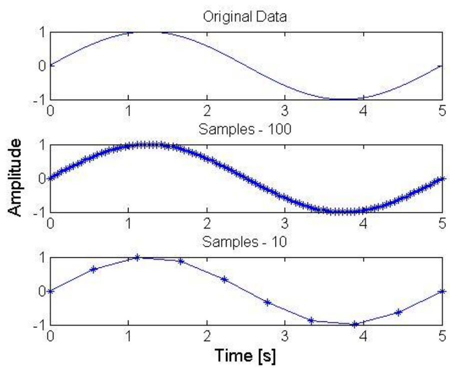
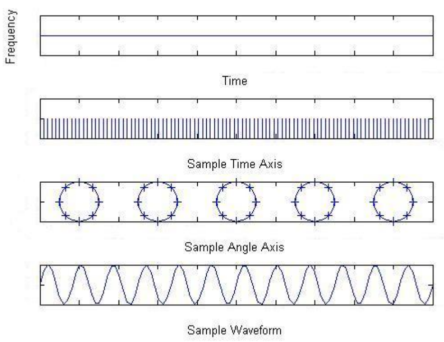
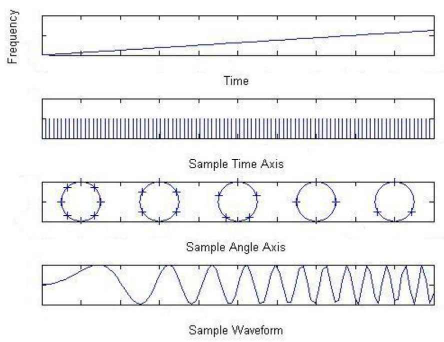


Figure 1.2 Resampling with different numbers of samples per revolution

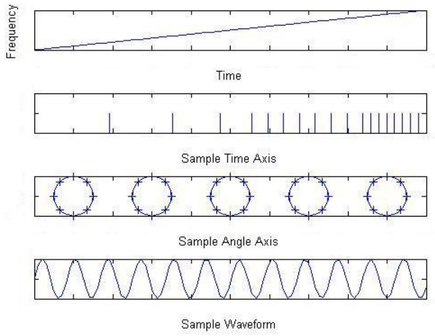
From Figure 1.2, it can be seen that with the decrease of the number of samples per revolution, the accuracy of the re-sampling result decreases. This is obviously not good for the accuracy of the final results. Since the re-sampled data will be further subjected to Fourier analysis, the more the deviation from a sinusoidal wave, the more order peaks will appear in the final order spectrum map. But all these are due to the low number of sampling points instead of real physical phenomena. Thus, as can be expected, more re-sampling points are desirable for accuracy. Some other influence factors, such as keyphasor timing accuracy, multiple keyphasor pulses, interpolation methods, etc. also definitely influence the final result and have been extensively discussed in literature (see for example Fyfe & Munck, 1997).

Based upon the above analysis, despite the constant speed assumption, COT is nevertheless a very useful order tracking technique. From the non-stationary rotational speed point of view, computed order tracking can effectively transform time domain data to angle domain data. Blough (2003) uses a graphic representation to explain this transforming process on a simple sine wave, as is shown in Figure 1.3





(a) Note: Constant $\Delta t =$ Constant $\Delta\theta$ (b) Note: Constant $\Delta t \neq$ Constant $\Delta\theta$



(c) Note: Variable $\Delta t \rightarrow$ Constant $\Delta\theta$

Figure 1.3 Sampling illustration in the time and angle domain with stationary and varying frequencies

Figure 1.3(a) represents the case for a stationary frequency sine wave sampled with a constant Δt. Figure 1.3(b) is the case for a varying frequency sine wave sampled with a constant Δt. Figure 1.3(c) is the case for the same varying frequency data re-sampled with a constant $\Delta\theta$. Clearly, the re-sampled data have properties similar to a stationary sine wave sampled with uniform time intervals. Both Figures 1.3(a) and 1.3(c) finally represent a periodic sine wave. It is interesting to see that the non-stationary sine wave in the time domain (Figure 1.3(b)), has been transformed to the stationary angle domain (Figure 1.3(c)). This uniformly spaced angle domain data is suitable to be processed by using the Fourier Transform to obtain amplitude and phase estimates of the orders of interest. This implies a clearer analysis of the signal using the Fourier Transform and also indicates that the re-sampling can be applied to harmonic waves and is not confined to the data that re-sampled through rotational speed. This characteristic is used in the ICR technique presented in this research. However, it is not difficult to see that COT does not address the quality of the raw data. Imperfections, such as distorted harmonic waves and noise, continue to exist after re-sampling process.

b. Current research on COT

In the literature, there are several papers regarding with the choice of parameters of COT. For instance, Fyfe and Munck (1997) studied the method in detail to examine which factors or assumptions have the greatest effect on the accuracy of COT. They find that this method is extremely sensitive to the timing accuracy of the key phasor pulses and also point out that high order interpolation in the process of re-sampling will greatly improve the spectral accuracy. Similarly, Saavedra and Rodriguez (2006) use data from various simulations to assess the effect of the assumptions inherent in the COT on accuracy and determine the effects of different user-defined factors: the signal and tachometer pulse sampling frequency, the method of amplitude interpolation and the number of tachometer pulses per revolution. Liu and Jiang (2007) also do something similar in discussing the principles of how to select the parameters in COT.

Some researchers compared different order tracking methods with COT. Bossley et al. (1999) comprehensively study three different synchronous sampling schemes: the traditional hardware solution, computed order tracking and a hybrid of the two. The three methods are assessed on data produced from a simulation of the coast down of a gas turbine shaft and therefore allow for studies of various interpolation algorithms. This ensures that the most appropriate algorithms are identified and COT is found to be superior.

Some researchers also focus on the implementation of this technique in real applications. Li (2007) develops a new method of combining COT and bi-spectrum analysis to detect gear crack faults in a gearbox under non-stationary run-up conditions. The experimental results show that order tracking with the bi-spectrum technique can effectively diagnose the gear faults. He, Zhang and Wen (2007) study fault issues of gear wear phenomena by using the COT technique. Their experimental studies prove that COT has the ability to detect the fault issue of gear wear and compared with the traditional spectral analysis, COT presents several advantages. Eggers, Heyns and Stander (2007) study COT to detect gear condition in a bi-directional rotating mine dragline. Various speed interpolation methods are used to realize COT. Their studies show that COT can be successfully employed in real environments. Guo, Chi and Zheng (2008) use independent component analysis (a statistical method), to reduce the non-order noise for COT analysis and analysis results show the present approach is useful for fault diagnostic applications of rotating machinery.

1.3.2 Vold-Kalman filter order tracking

VKF-OT is a comparatively new technique. It was first adapted to order tracking by Vold and Leuridan (1993). It is a fundamentally different method from Fourier Transform based order tracking and computed order tracking. During the past seventeen years, many researchers like Vold, Mains and Blough (1997), Vold, Herlufson, Mains and Corwin-Renner (1997), Feldbauer and Holdrich (2000), Tůma (2005), Pan and Lin (2006), etc. have reported on the theory of VKF-OT. The characteristics of Vold-Kalman filter order tracking have been presented by Herlufsen et al. (1999). Recently, the main principles and limitations of current order tracking methods have been summarized by Brandt et al. (2005) where the VKF-OT is also discussed as a main theme. Its fundamental theory has therefore become much clearer to the engineering community. Some companies have commercialized this technique into their software, e.g. Brüel & Kjær and MTS Testing Solutions. Brüel & Kjær develops the Vold-Kalman order tracking filter into a commercial product and states that VKF-OT allows high-performance tracking of harmonic responses, or orders, of periodic loads in mechanical and acoustical systems. This method allows beat free extraction of close and crossing orders in systems with multiple shafts, and features a finer frequency and order resolution than conventional techniques. The product material of Brüel & Kjær also documents the advantages of this kind of order tracking method compared with the computed order tracking method, as that of much shorter transients, no phase bias, no slew rate limitations and order information which can be extracted in the time domain. Blough (2003) points out that one of the key advantages of the second generation Vold-Kalman filter is the lack of constraints on frequency and slew rate. However, Wang and Heyns (2008) point out that during the filtering process, the filtered time domain order waveforms will retain the non-stationary frequency effect as in the raw data. It is therefore not suitable for further Fourier analysis, which is inferior to the COT in this regard. It should also be borne in mind that since the original VKF-OT requires longer computational time due to its mathematics, it is therefore not usually used in online monitoring. Quite recently however, Pan and Wu (2007) proposed an adaptive Vold-Kalman filtering order tracking approach to overcome the drawbacks of the original VKF-OT scheme for condition monitoring on this issue. Their work solves the problem and gives a good accuracy with reasonable computational time for VKF-OT. This makes the technique a more practical and powerful tool and renders online condition monitoring by using VKF-OT possible and feasible.

Tůma (undated study notes) shows that the Vold-Kalman filter is based upon so-called data and structural equations, with both of these equations that are excited by unknown functions on the right hand side. In his study notes, both the first and second generation Vold-Kalman filters as well as their differences are explained clearly in terms of the mathematics. The main difference between the two generations lies in the formula of the data and structural equations. In the first generation Vold-Kalman filter the amplitude and phase modulated order signal is described in a general term, such as $x(n)$. However amplitude envelope and phase for an order signal are considered separately in the second generation of Vold-Kalman filter order tracking, such as $x(n)e^{j\Theta}$ where $x(n)$ does not represent the whole order vibration any more but order envelope. Although $x(n)$ in first generation and $x(n)e^{j\Theta}$ in the second generation look different in their form, however they are essentially the same and both represent an order vibration. Further, Tůma (2005) presents a paper to deal with the often-neglected issue of setting the filter pass band, which is fundamental to the theory of his MATLAB scripts.

In essence, Herlufsen et al. (1999) argue that the Vold-Kalman filter defines local constraints, which require that the unknown phase assigned orders are smooth and that the sum of the orders should approximate the total measured signal. The smoothness condition is called the structural equation and the relationship with the measured data is called the data equation. In this paper, they discussed characteristics of one, two and three pole Vold-Kalman filters which is a guideline for the choice of suitable pole number for Vold-Kalman filter.

Wang (2008) summarizes in his master's dissertation, what VKF-OT is and how to implement it. He essentially develops a whole package of Vold-Kalman filter application procedures which demonstrate the mathematical fundamentals as well as the choice of filter bandwidth. This forms the basis of the working algorithm and MATLAB scripts that are used in the Vold-Kalman filtering applications in this work. While Wang also mentions that this package is not the only route to the application of VKF-OT, it provides a good introduction to this technique.

Relating to VKF-OT applications, Guo, Tan, Huang and Zhang (2008) use the independent component analysis method to remove crossing noise in VKF-OT so that it overcomes traditional problems for cross-noise decoupling.

The application of VKF-OT on real machinery however is still in the initial period. Not many papers deal with the application of this technique. Pan and Lin (2006) published a comprehensive paper about VKF-OT. They explain the detail of the theory of VKF-OT in two different settings, namely, angular-velocity VKF-OT and angular-displacement VKF-OT. Further they examine the effectiveness of applying the theory in their experimental work. In 2008, Pan, Li and Cheng (2008) established a whole package for a remote online machine condition monitoring system. In their package, VKF-OT is also used as a key signal processing method to diagnose machine conditions. Recently, Wang and Heyns (2009) studied the choice of Vold-Kalman filter bandwidth in a simple rotor simulation model and further apply the VKF-OT technique in condition monitoring of an automotive alternator stator with faults. The result shows that the VKF-OT is an effective method in condition monitoring.

Based upon the preceding literature survey, it is not difficult to conclude that VKF-OT is an effective and promising tool for condition monitoring rotating machinery, and is clearly one of the best available techniques for performing order tracking. But it needs more research on full practical utilisation of the technique, as well as simplification for new users.

1.3.3 Intrinsic mode functions through empirical mode decomposition

In 1998, Huang and his colleagues (Huang et al., 1998) proposed a novel approach called the Hilbert-Huang transform (HHT) for analysing nonlinear and non-stationary signals. The key part of the method is the empirical mode decomposition (EMD) with which any complicated data set can be decomposed into a finite and often small number of intrinsic mode functions (IMFs) that permits well-behaved Hilbert Transforms.

With EMD, any complicated signal will be broken down into a finite number of IMFs based on the local characteristic time scale of the signal. The IMFs represent a collection of natural oscillatory modes embedded in the signal, from high frequency to low frequency. Originally, IMFs were viewed as mono-components representing some intrinsic physical meaning and making sense of instantaneous frequency for further Hilbert Transformation. The idea of mono-components however is arguable. Cohen (1995) first introduces the term but does not give a clear definition. For lack of precise definition, the narrow band component defined in the book of Schwartz, Bennett and Stein (1966) is therefore adopted as an alternative way to describe IMF. This makes the EMD process more like a group of narrow band filters, and the method can therefore be treated as a self-adaptive dyadic filter bank (Flandrin, Rilling and Gonçalvés, 2004) which allows each IMF to be determined by the signal itself rather than pre-determined parameters. During the past few years, the HHT and the EMD method have been studied extensively in theory and applications. Unfortunately, there is still no single universally recognized precise mathematical definition for the HHT and EMD.

However some serious mathematical works on its fundamental theory are now available. These include work by Rilling, Flandrin and Gonçalvés (2003, 2004), Daetig and Schlurmann (2004), Sharpley and Vatchev (2006), and Feldman (2008). Very recently, Feldman (2009) further studied the characteristics of the EMD method. He analyzes the very special and useful case of decomposition of two harmonics which sheds some light on the nature of the resolution of each IMF. He describes in his paper the analytical basics of the EMD method and presents a theoretical limiting frequency resolution for EMD to decompose two harmonic tones. This undoubtedly helps a great deal to understand the resolution of EMD as a filter bank. He mentions that frequency and amplitude ratios of two harmonics can be separated into three different groups, to evaluate the resolution of the EMD method for two harmonics and plot these on 2-D and 3-D graphs which enrich the understanding of the fundamentals of resolution for EMD and is a useful contribution in the theoretical study of EMD.

Another important contribution was made by Huang, Wu and Long (2006) who developed an iterative normalized scheme, enabling any IMF to be separated empirically and uniquely into envelope (Amplitude Modulation (AM)) and carrier

(Frequency Modulation (FM)) parts, which resolve many traditional difficulties associated with instantaneous frequency. The technique is therefore called empirical AM/FM demodulation. However, the empirical FM part may contain riding waves and is no longer an intrinsic mode function, which renders the instantaneous frequency nonsensical. (A riding wave is defined as follows: In a signal, if there exists a local minimum greater than zero between two successive local maxima, or if there exists a local maximum less than zero between two successive local minima, the segment between these two successive local maxima (or local minima) is called a riding wave (Yang, Yang, Qing and Huang, 2008). In the paper, there are several examples of riding waves and the existence of riding waves violates the definition of an IMF.) To overcome this drawback, Yang, Yang, Qing and Huang (2008) improve the empirical AM/FM demodulation method into a riding wave turnover-empirical AM/FM demodulation and their experiments show positive results.

Rato, Ortigueira and Batista (2008) review some important questions related to the effective performance of the EMD method. Some drawbacks of EMD are put forward and solutions for these drawbacks are proposed. Numerical simulations are also carried out to empirically evaluate the proposed modified EMD method. This work provides comprehensive guidelines to understand the pros and cons of the EMD method.

In recent years, there have been many papers discussing the application of HHT or EMD in real machinery problems, simulation studies and practical signal processing. For instance in some real machinery problems, Liu, Riemenschneider and Xu (2006) apply HHT to vibration signal analysis for localised gearbox incipient tooth crack fault. The results show that the EMD algorithms and the Hilbert spectrum perform excellently and find that this technique is more effective than the commonly used continuous wavelet transform in the detection of vibration signatures.

Rai and Mohanty (2007) use the Fast Fourier Transform (FFT) of intrinsic mode functions in EMD, to enhance the ability of detecting incipient bearing faults. Their analysis results indicate the effectiveness of using a frequency domain approach in EMD and its efficiency as one of the best-suited techniques for bearing fault diagnosis.

Gao, Duan, Fan and Meng (2008) also investigate the EMD approach for rotating machine fault diagnosis. In their research, they show that IMFs sometimes fail to reveal the signal characteristics due to the effect of noise and hence they develop the combined mode function (CMF) method, which combines the neighbouring IMFs to obtain a more precise oscillation mode. Finally, they apply EMD and CMF methods to a practical fault signal of a power generator. The results show that both of the techniques are effective.

Chen, Yu, Tang and Yang (2009) use EMD to diagnose local rub-impact in a rotor system. Local rub-impact faults in a rotor usually lead to amplitude-modulated vibration signals, which are however submerged in the background of noise. Their studies show that the EMD successfully extracts the modulated vibration signal from local rub-impact, while there are no distinct amplitude-modulated characteristics of the vibration signals under conditions without local rub-impact. It is therefore concluded that the EMD method can be effectively applied for local rub-impact fault diagnosis.

Wu and Qu (2009) mention in their paper that in practice most sub-harmonic signals are closely related to time variables and can manifest in large amplitude fluctuation, transient vibration or modulation signals in the time domain. Therefore, they use the EMD method to extract intrinsic mode functions from some actual vibration signals to diagnose malfunction in large rotating machinery due to rotating stall and pipe excitation related problems in the system. They conclude that the EMD method provides an attractive alternative to the traditional diagnostic methods.

For some simulation and signal studies, Chen, Yan and Jiang (2007) propose a dynamic-based damage detection method for large structural systems using HHT. Their method is verified numerically by implementing the scheme on a model of a wing box and the results show that the proposed damage detection method is very robust.

Guo and Peng (2007) establish a finite element rotor model with a propagating transverse crack. By analysing the start-up transient response of a rotor, they demonstrate that the HHT is an effective tool for the analysis of non-linear, unsteady transient vibration response.

Li and Meng (2005) study the capability of the EMD method to extract a harmonic signal from a chaotic background. Since numerous observable chaotic signals can be detected in real-world data, such as electrocardiograph signals, extracting a harmonic signal from a chaotic signal becomes very important. They generate a harmonic signal contaminated with a chaotic interference introduced by a Duffing oscillator, and then use the EMD method to extract the harmonic signal from the chaotic interference. Their simulation results show that the harmonic signals can be effectively recovered from the contaminated signals by the EMD approach.

Li, Deng and Dai (2006) develop a technique that combine EMD and wavelet transform to detect the changes of structure response data. By using different test models, they demonstrate that combining EMD and continuous wavelet transform can be used to identify the time at which structural damage occurs more sharply and effectively, than by using the wavelet transform method alone.

1.4 Scope of work

Based upon the problem statements and the literature surveys presented above, it is now necessary to explain the inter-relationship of the three different order tracking techniques and their usefulness in condition monitoring of rotating machines, to further understanding of the significance of this work. In fact, the three improved order tracking approaches have not been chosen arbitrarily, but are based upon the inter-relationship between the order tracking techniques under consideration. The advantages and limitations of each of these techniques are explored above in paragraph 1.2. Figure 1.4 below depicts the relationship of three approaches developed in Table 1.1 in terms of different kinds of arrows that indicate the different relationships between techniques, so that one may have a better idea of how this work integrates these techniques. The following explanation of each approach further highlights the possible benefits in condition monitoring and renders novel methods that will be thoroughly discussed in the thesis.

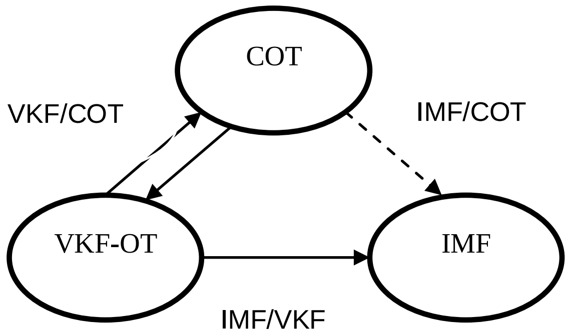


Figure 1.4 Integrating three independent order tracking techniques

VKF/COT $\rightarrow$ VKC-OT

The two way solid arrows linking VKF-OT and COT emphasize that VKF-OT and COT are indeed complementary to each other, each with distinct advantages and disadvantages which make up for each other. The VKF-OT advantage of focusing on individual orders and the COT advantage of excluding frequency variation may be combined. The VKF-OT disadvantage of frequency variation which remains in the filtered time domain signals and the COT inability to focus on one individual order may therefore also be overcome. This is why the idea of combined use of these two order tracking techniques is developed in this work. This approach is of significant importance in real applications. In condition monitoring, focusing on an order signal while simultaneously excluding the effect of speed variation from the order spectrum, definitely enhances the ability of specific orders in condition monitoring for rotating machinery. Vold-Kalman filter and computed order tracking, VKC-OT, is therefore presented to fulfill this requirement.

IMF/VKF $\rightarrow$ IVK-OT

The one way solid arrow linking VKF-OT to IMF explains that the VKF-OT results may belong to the set of IMFs from EMD, in other words, VKF-OT results can be a subset of the IMFs. Each IMF may include one or more orders by the filtering of Vold-Kalman filter. Thus, through subtracting VKF-OT results from an IMF, the separation or differentiation on an IMF becomes possible. Therefore, in this work, VKF-OT will be used to assist further decomposition of IMFs in terms of rotational speed. Then, the sequential use of IMF and VKF-OT (IVK-OT) is developed. Again for condition monitoring purposes, this further decomposition process is of great practical importance. The VKC-OT discussed above, emphasize examining specific orders of interest. As a result, it may lose the ability to examine vibration signals that modulate orders. However, machine faults may result in unpredictably complex vibrations. They may be synchronous or non-synchronous with the rotational speed and modulate dominant order signals, By means of an example a rub-impact of a rotating machine may lead to a complex nonlinear vibration response. Evidently vibration signals that modulate orders are critical information for condition monitoring and not necessarily synchronous with rotational speed. Therefore, to separate and study these vibrations provide additional useful information for machine fault diagnostics. The IVK-OT may therefore serve as a means for analyst to discover this useful information in IMFs.

IMF/COT $\rightarrow$ ICR

The one way dashed line arrow between COT and IMF indicates that the two methods are not directly related. However, due to the simple special data structure of an IMF (this will be further explained in chapter 2, paragraph 2.3), the core re-sampling idea of COT that transforms signals from non-stationary to stationary, may be borrowed into an IMF. And therefore speed variation effects in an IMF can be largely excluded, so that an empirical approximation of computed order tracking effects without the aid of rotational speed can be achieved. Thus in this work, a novel reconstruction procedure of an IMF will therefore be developed, namely intrinsic cycle re-sampling method (ICR). Two aspects are considered advantageous in this technique. Firstly, for order tracking analysis a technique which does not require measured rotational speed is of great practical use. Secondly, it is known that IMFs may include abundant machine fault information. If made more readily available in practice through simplified analysis, approximate order analysis may most likely enhance machine fault diagnostic ability and therefore offers an alternative condition monitoring method worthwhile to explore. Indeed, this technique provides a good alternative approach to condition monitoring. This is demonstrated in simulation and experimental studies in chapter 3 and 4 where the ICR method is used to monitor gear mesh faults.

In short, three independent order tracking techniques are integrated to capitalize on their distinct respective advantages and offset their disadvantages. These integrations are all based upon their potential practical significance for condition monitoring. In the following chapter the focus will be on the developments of three order tracking improved approaches. Then, simulation and experimental studies will prove the effectiveness and usefulness of these improvements.