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Physics-Based Simulation for Health Management of Rotating Machinery

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Abstract

Data-driven techniques for diagnosing faults in rotating machinery have a long history. Such approaches undoubtedly have their strengths and much research is still being performed in this area - recently into gearbox and bearing faults in particular. However, with the increasing power and sophistication of simulation tools, new methods for diagnosis, localization and prognosis of faults are rapidly being researched. This paper outlines current developments in modeling and simulation for rotating machinery health management and discusses the potential for such technologies to move from the realm of research into live systems. Comparisons and synergies with traditional data driven methods are made and it is concluded that simulation-driven techniques have much potential for next generation PHM systems.

1. Introduction

The diagnosis of faults in rotating machinery is an ongoing topic of research. Data-driven techniques have historically been at the forefront of this research, and continue to play a key role in the diagnosis and prognosis of a wide range of rotordynamic faults. Although the need for such data-driven methods is clear, recent developments in physics-based simulation have enabled different approaches to rotordynamic problems to be formulated.

An example of an obvious advantage of physics-based simulation can be found in the diagnosis and prognosis of crack growth, where finite element analysis (FEA) techniques have already saved industry large sums of money. Simulation-based diagnostics and prognostics are, however, not limited to areas such as this. The aim of this paper is, therefore, to discuss current developments in the field of physics-based simulation for diagnosis, prognosis and localization of rotordynamic faults and to discuss the potential for future implementation of such research.

The area of rotordynamic faults is a diverse one, where many types of fault can occur in many different kinds of machine. It is not pertinent to cover all potential rotordynamic faults, and instead a selection of the more common faults is described with regard to diagnosis using simulation techniques. The selected faults are unbalance, misalignment, rub and looseness, fluid-induced instability, bearing faults, shaft cracks, rotor cracks and rotor bow. These faults have been chosen due to being some of the more common problems which can occur in most types of rotating machinery, and the interlinking nature between them (for example, a misalignment may lead to an unbalance).

2. Rotordynamic Faults

The following section details the afore-mentioned common rotordynamic faults with regard to recent physics-based simulation work and traditional data-driven methods. Research in this area of rotordynamics is particularly widespread, and so this paper outlines only a few recent areas of research.

2.1 Unbalance

This is one of the most common rotordynamic faults (1); every rotating machine has an inherent degree of unbalance. Unbalance as a fault can, therefore, be defined as unbalance outside of a given tolerance level. A recent piece of research which demonstrates the ongoing development of data-driven techniques is that by (2), who tested a technique for measuring operating deflection shapes in order to detect unbalance cases. These studies were conducted on a machine fault simulator – such simulators have the advantage of recreating faulty conditions quickly and easily, enabling a new dimension to data-driven diagnostic techniques. It is, however, worth mentioning that data for these experiments were collected using 14 accelerometers, which are easy to apply to such a simulator, but it may be much more difficult to configure this many sensors on a complex system.

Regarding physics-based simulation of unbalance as a fault, the work by (3) involved creation of a virtual bearing-shaft-rotor system, not dissimilar to the aforementioned machine fault simulator. Modeling and simulation was performed using ADAMS, demonstrating an efficient way to simulate and practice machine balancing without the need for alterations to real systems. It is of note that the authors of this paper stress the need for experimental data in validating their results, indicating the synergy required between data driven and simulation-based methods.

Localization and prognosis of unbalance pose a unique set of challenges, and as a result research is still somewhat limited in these areas. One recent work which claims to localize unbalance accurately is (4), the authors of which use trending data and reasoning systems to locate localized unbalance and shaft bow across a system. Remaining useful life of unbalance is difficult to predict due to complicating factors. An unbalance may, for example, be a result of a misalignment or bearing fault – which could be considered a root cause. A misalignment may lead to unbalance which induces a rotor-stator rub. Such combinations of faults and underlying causes for unbalance lead to the need for remaining useful life predictions to be made based upon the exact nature of a specific fault.

2.2 Misalignment

This is another common fault which can potentially inflict considerable damage in rotating machines. As with unbalance, misalignment in a whole system can be complicated by secondary faults (e.g. a misalignment which causes a rub). Reference (5) is an interesting paper in this area due to the author considering unbalance, misalignment and cracks to produce a piece of software which will identify and differentiate these faults. It is claimed that the software is easily adaptable between different systems.

Reference (6) demonstrates interesting research into misalignment from the perspective of physics based simulation. The authors construct mathematical models of a simple rotor system with a misaligned coupling and collect harmonic response data from this to assess the severity of different misalignment cases. Such models are useful throughout the life of rotating machines – from design to implementation, although again successful validation with experimentally obtained data is key.

As with unbalance, localization and prognosis of misalignment is a complex topic to research. Studies such as (6) can make accurate predictions for misalignment in a simple system with one coupling. However real systems (e.g. aircraft gas turbines) have many potential locations of misalignment. This is an area where few researchers have made an impact. Remaining useful life predictions for misalignment are complicated for the same reasons as with unbalance. Reference (7) is notable for construction of a prognostic health management system for flexible power transmission couplings. The authors use a combination of data driven and modeling methods, including finite element techniques and claim a 15% increase in accuracy over purely data-driven methods.

2.3 Rub & Looseness

Rub is always a secondary fault (i.e. a product of another fault such as looseness) and can lead to fatigue and wear. Rub and looseness can create complex vibration signals which are difficult to diagnose using traditional methods. Modeling and simulation of rub and looseness faults have been considered in several recent works. This includes (8), which outlines a dynamic system model of a rotor-bearing-stator system embedded with a rubbing fault. This work is particularly interesting as it takes into account vibration signatures of a whole aero-engine, an important consideration if such research is to move into industrial applications. Reference (9) is a good example of how simulation techniques can complement data-driven methods. The authors of this work outline a finite element model of a dual-disk rotor-bearing system which incorporates a looseness-induced rub. The model is used to predict vibration signatures of such a rub, which can then be combined with trending data to produce a diagnostic system.

Localization of rub and looseness across whole systems is relatively lightly studied in literature. Many works (including those already cited) look at single or dual-rotor systems where localization of such faults is not an issue. In an industrial setting, complex systems may comprise many rotors in several compressor and turbine stages, significantly complicating diagnosis of such faults. Research into prognosis of rotor-stator rubs lies mostly within the domain of data-driven techniques. Modeling and simulation research can be used to support data-driven techniques for prognosis and condition-based monitoring. Reference (10) is an example of this; the authors use finite element modeling to construct a dual rotor model. Various types of rub-impact are then studied. Such studies can provide a wide range of information, which can then be combined with data obtained from live systems, potentially with seeded faults, in order to construct accurate remaining useful life predictions.

2.4 Fluid-Induced Instability

Fluid-induced instabilities (often referred to as whip and whirl) are potentially very serious faults which can result in wear, fatigue and extensive damage to machine components. Such instabilities can be found in interstage seals, fluid lubricated bearings and blade-tip clearances. Research into simulating and modeling fluid-induced instability has produced several works of interest to fault diagnosis of rotating machines in the last few years. Reference (11) is a good example, where non-linear mathematical models are prepared for a rotor-bearing system. The models are then used to predict instability thresholds. Another good example is the extensive numerical analysis carried out by (12), which results in a system for diagnosing faults including rub and fluid-induced instability, validated against experimental results.

Prognosing fluid-induced instability is a relatively lightly researched topic. Fluid instabilities can be covered as part of extensive research into remaining useful life of bearings. The potential exists for modeling and simulation techniques such as those detailed above to become a part of prognosis for fluid induced instabilities due to the fact that it can be very difficult to seed such faults into live systems for testing and evaluation. As with other faults detailed in this report, many studies have been performed with the aim of describing fluid-induced instabilities based on the measurement or simulation of single (or occasionally dual) rotor setups. Physics-based simulation with the aim of localizing fluid instability faults across a whole system can be limited by the complexity of both the fault and the system, hence, the simplification to single rotor-stator bearing systems.

2.5 Bearing Failure

An area where data-driven techniques are still providing the basis of much research in the field of rotordynamics is that of bearing failure. The title ‘bearing failure’ can cover a wide range of potential issues which continue to be studied in detail. Faults can occur in all parts of engine bearings – the inner and outer case, the cage and the rolling elements. Data-driven techniques have enabled accurate bearing diagnostics and prognostics to be described for a range of rotordynamic systems.

Despite the prevalence of data-driven research in this area, research from a physics-based simulation perspective has also recently produced some interesting papers of relevance to condition monitoring and health management of rotating machinery. This includes (13) who detailed a selection of aero engine bearing faults and their consequent effects on a rotor. Reference (14) is a good example of high fidelity modeling for bearing faults. The authors comment on and suggest tradeoffs between computational time and accuracy – always an important factor in computational fault models.

As so much research has been performed (and is ongoing) into bearing faults across a wide variety of mechanical systems, both prognostics and localization of bearing faults have been researched in somewhat more detail than some of the other faults detailed here. Despite this, much work still needs to be performed in order to translate some of this core research into industrial applications. Research such as that detailed above has made significant advances into determining bearing failure as the root cause of a malfunction. Detecting which bearing is failing across a complex system has received somewhat less research. Bearing prognostics is another area with much ongoing research being performed – both in the simulation and data-driven domains. To give an example, (15) combined grade life and extensive mathematical modeling techniques in order to produce prognostic models for aero engine bearings. Reference (16) is an example of pure data-driven techniques, the authors of this work making comparisons between traditional fast Fourier transform (FFT) analysis and enveloping techniques, again for use in aero engine bearing prognostics.

2.6 Shaft Cracks

Another potentially serious fault in rotating machinery is shaft cracks, and so early detection of any such fault is highly important. Methods of crack formation and propagation can be diverse, and range from high and low-cycle fatigue to stress corrosion. Simulation and modeling of shaft cracks can have significant advantages over data-driven methods. Perhaps the most obvious advantage is the relative simplicity of inserting a fault into, for example, a finite element model as opposed to seeding a fault in a working industrial machine. As such, research into shaft cracks has been progressing steadily with the corresponding increases in computing power.

A clear synergy between data-driven and physics-based simulation research can be implied by a number of recent works of research. An example of recent advances from a data collection perspective is (17), which details statistical models based on historical data for condition monitoring purposes. From a modeling perspective, (18) used finite element analysis to assess shifting natural frequencies, which are then combined with pattern recognition techniques.

The nature of shaft cracks has resulted in a wide variety of research being performed into both localization and prognostics of these faults (indeed, the two topics can be considered related). Recent examples of work in this area include (19), which details crack localization using forced response modeling. Reference (20) describes finite element modeling of crack propagation, with validation against experimental results provided to demonstrate the validity of such modeling techniques.

2.7 Rotor Cracks

Rotor cracks, if allowed to develop, can result in serious consequences. Cracks can form due to high centrifugal stresses across operational cycles (in the case of an aircraft gas turbine, for example, start up and take off through landing and taxi). As excessive crack growth can lead to catastrophic rotor/blade failure, early detection and prognosis of such faults are essential (21). As with shaft cracks, physics driven simulation of rotor cracks is an area of significant research. This varies from high-fidelity finite element models to low-fidelity system and mathematical models. The recent work demonstrated in (22) is a good example of recent mathematical modeling from a diagnosis perspective. Reference (20) demonstrated high fidelity modeling, the authors used FEA to model crack growth, making comparisons and validating against an experimental rig. This work is particularly interesting as it outlines the advantages and drawbacks with the latest state-of-the-art modeling techniques.

Localization and prognosis of rotor cracks have also benefitted from recent advances in simulation and modeling. Reference (23) contains details of work on a novel active magnetic bearing system for use in the early detection, localization and prognosis of rotor cracks. FEA has also been used extensively to support rotor crack prognostic tools; (24) is an extensive example of recent work.

2.7 Rotor Cracks

Rotor bows can be a primary source of unwanted vibration in gas turbines. The main cause of a rotor bow (rotor bows do not include bows due to gravity) are thermal differences in a system caused by operating conditions. It is noted in (1) that this nonsymmetrical thermal distribution can cause excessive unbalance to the extent where a gas turbine will not start correctly. Such rotor bows are common on start up or shut down, and are often accounted for in operational procedures. However, if thermal ‘hot spots’ exceed a given tolerance level, they can cause permanent unbalances due to rotor deflections. Such rotor bows can lead to other faults, including rubbing and looseness which complicate isolation and localization.

Traditional data-driven techniques for detecting rotor bows involve combinations of slow roll and vibration data (26). More recently, mathematical modeling techniques such as that detailed in (26) have been used in order to diagnose residual rotor bows, and differentiate these faults from other sources of unbalance.

The little work that exists on attempting to localize rotor bows across complex systems tends to be data-driven in nature; see (27) the authors of which used statistical symptoms based on known data as a method of diagnosing and prognosing a number of faults, including rotor bows and unbalance. Prognosing rotor bows is a complex subject. As rotor bows are often caused by temperature deflections, making predictions for remaining useful life and potential future problems lies not only in the realm of mechanical rotordynamics but also to some extent in thermodynamics. The recent work detailed in (28) is of note for detailing diagnosis and quantification of various rotordynamic faults and describing the advantages of mathematical modeling over traditional vibration-based approaches. Another two works which are of interest with regard to modeling of rotor bows include (29), the authors of which modeled a rotor-bearing system with a permanent rotor bow, looking at the impact of secondary faults such as rub. Reference (30) describes the importance of model-based fault identification techniques and outlines recent research in the area.

3. Diagnosis

It can be seen from the research outlined in the previous section that the diagnosis of faults in rotating machinery is a subject of ongoing research. This involves the improvement and development of traditional vibration monitoring techniques, development of new data-driven technologies and novel research into physics-based simulation and modeling. In many cases, these topics of research are dependent on one another for reasons of validation, verification and speed of analysis. In several cases it can be seen that multiple faults have been modeled for the purposes of identification and isolation. However no studies have yet been performed which deal with all of the afore-mentioned faults. All of these faults are intrinsically related to one another. Complex combinations of faults have begun to be analyzed with the emphasis on developing new diagnosis techniques. Physics-based modeling has proven to provide significant advances with regard to specific faults, notably shaft and rotor cracks, where techniques such as FEA enable much easier, faster and cheaper test data then seeding faults into live systems.

It can be noted, however, that both high and low-fidelity modeling techniques are being applied to cutting edge research for all of the listed rotordynamic faults (and others not detailed in this paper). In addition to the advantages in the speed of obtaining test results, physics-based simulation is providing another dimension to data-driven techniques. System models are being used as part of logic and reasoning suites in the identification and differentiation of various faults. High-fidelity models enable simulations of fault combinations for which is it not possible, practical or is prohibitively expensive in live systems.

Nevertheless, results obtained from modeling studies still need to be validated against proven data-driven techniques before implementation in industrial applications is possible. It is also of note from the literature reviewed for this paper that almost all modeling for the diagnosis of faults involves extensive simplification, often reducing potentially complex systems down to one or two rotor/shaft/bearing models. Adapting the claimed results from such research to systems with many rotors/bearings/shafts is important in improving existing rotating machinery diagnostic techniques.

4. Fault Localisation

Fault localization in rotating machinery is an important topic of research for future condition-based monitoring systems. Knowing not only what type of fault has occurred, but also where in the system is an important consideration which can influence maintenance procedures in complex machinery. It is worth noting from the literature surveyed for this paper that many studies have focused on diagnosis and prognosis of single rotor/bearing systems. Often for legitimate reasons – simplification for computing speed, for example. Few studies, however, have taken into account the localization of faults across whole systems. This problem is not limited to modeling and simulation-based research. Many newly-developed data-driven techniques for diagnostics and prognostics claim good results by heavily instrumenting specific components of a test system. In many industrial cases this is not possible, practical or cost effective.

To give some examples: a keyphasor transducer can be particularly useful in diagnosing faults such as rotor bow. However, this equipment requires the ability to cut a keyway for measurements to be performed. Optical sensors have recently been applied to detect rotor unbalance; yet such a technology would be difficult to implement in a system with several rows of rotors (as in a gas turbine).

Whilst new diagnosis and prognosis techniques for faults in rotating machinery are being continuously researched, the lack of corresponding studies into localization can be considered one of the many challenges in promoting recent core research into live industrial applications.

5. Fault Differentiation

One promising development in recent modeling and simulation of rotordynamic faults is that of fault differentiation. Several researchers have moved on from studies on individual faults in order to concentrate on combinations of faults. As stated, rotordynamic faults such as those listed in this paper are linked to each other. Such studies, therefore, concentrate on such topics as a misalignment causing an unbalance or a looseness causing a rub. Findings from reports such as these are important in understanding complex anomalies. In industrial applications, simply detecting and rectifying an unbalance does not provide a satisfactory solution if the root cause of the fault is a misalignment. This is a complex topic, as several faults can exhibit similar vibration characteristics, making traditional detection techniques inaccurate in some cases.

6. Prognosis

It can be seen from the examples of recent research described for common faults that prognostic techniques are a topic where much work is being performed. Whilst some of this work would be very difficult or impossible to implement in an industrial situation, others provide promising results of use to future work in the area. Predicting the remaining useful life of components is critical in the development of condition-based monitoring strategies for industrial implementation.

It can be noted that prognostic studies for certain rotordynamic faults are considerably more advanced than for others. The most obvious examples of the faults detailed in this paper are bearing faults, shaft and rotor cracks. These are also areas where physics-driven simulations have had an important impact. The ability to design any fault type (or combinations of faults) into such simulations (be it low-fidelity mathematical models or high-fidelity finite element analysis) has provided researchers with many different avenues to explore. Studies into the prognostics of other faults can be complicated by various factors. An unbalance, for example, has had relatively little research performed into prognosis. The fact that unbalance is often the cause of another underlying fault is one reason for the difficulty in researching prognosis in detail for this fault. The results of unbalance are also very dependent on the severity of the fault and the system in which is occurs.

Finally, it is worth noting that whilst combinations of faults have been simulated extensively for the purpose of diagnostics, few studies exist combining faults for the purpose of prognostics. Such studies are, however, a logical progression from some of those already performed.

6. Rotordynamics and PHM

The bulk of current research into rotordynamics from the point of view of prognostic health management (PHM) can be roughly divided into two types: initial single-fault diagnosis/prognosis techniques and studies into the general requirements and limitations of current systems along with current and future trends. An example of the latter is (31) who provides a good summary overview of current diagnosis and prognosis techniques with regard to condition-based maintenance.

As a result of this split, a clear gap exists between the core research being performed into rotordynamics from a condition-based maintenance perspective and the identified needs of industry. Taking a fledgling piece of research and applying it to a commercially-ready system (e.g. a gas turbine engine for an aircraft) is a long and complex task. It is nevertheless worth noting that technologies for automatically detecting an unbalance or misalignment in a gas turbine were developed over 10 years before the latest commercial aircraft were conceptualized, and yet these planes are still limited in this capacity. This highlights the need for work which links the fundamental research into individual fault diagnosis to ‘live systems’ in use in industry.

Physics-based simulation and modeling of rotordynamic parts is a well-researched field. Such modeling has been used as the basis of diagnosis and prognosis of faults by many researchers; several recent examples have been outlined in this paper. Occasional pieces of work have been performed into modeling multiple faults, such as (32) who use a system model for online identification of unbalance and cracks. Beyond this, however, very limited research exists. The demands of PHM systems in industry are such that any system must not only be capable of detecting multiple faults, but must also be capable of detecting these faults across a range of different systems. Other considerations include the afore-mentioned ability to differentiate between multiple faults. Processing also needs to be taken into account, as the objective of such systems is to implement efficient condition monitoring and condition-based maintenance procedures. If processing data is a long, power-hungry process then this aim cannot be achieved.

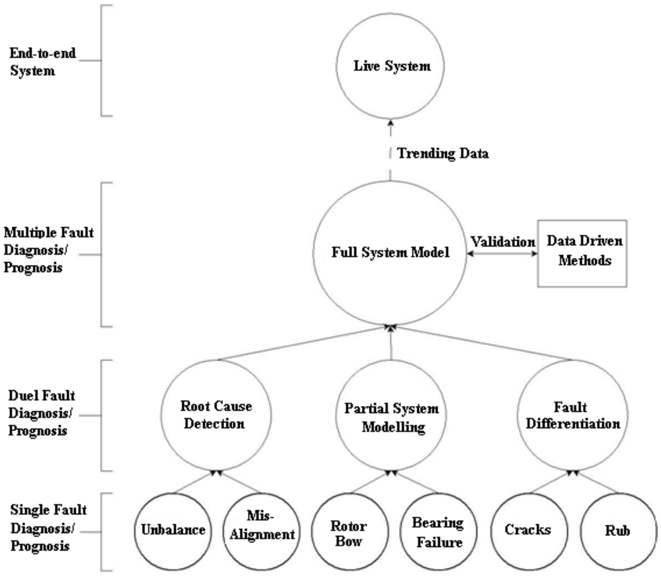

Figure 1. Physics based simulation – from research to industry

Figure 1 details a potential framework required in order to push core research, such as that detailed in this report, towards industrial applications. Many studies now exist on individual rotordynamic faults across a wide range of conditions and applications. Some studies have taken this further, with advanced prognostic models and diagnosis of dual faults (primary cause and secondary effect). Future research in the area of rotordynamics from a PHM perspective could potentially provide the bridge between these studies and live systems, by validating and combining with data-driven techniques.

6. Conclusion

It is clear that recent developments in physics-based simulation for rotating machinery health management have enabled another step to be made towards implementing PHM systems in many industrial applications.

Such modeling and simulation techniques have provided a new dimension in diagnosing, localizing and prognosing rotordynamic faults, in ways which data driven methods have not been able to.

Despite these advances, further research is required in order to implement these new technologies in industrial PHM systems. The need for research to be diversified from simple models with a single fault in order to cover whole, complex systems has been discussed along with the need for both simulation and data based research in achieving this aim.

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