

EFFECTIVE AND SIMPLE IDENTIFICATION INDICATORS OF DIFFERENT ROLLING BEARING FAULT TYPES

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ABSTRACT

The paper presents some effective frequency indicators of rolling bearing faults. These indicators are used to diagnose localized faults in rolling bearing elements. These faults usually cause strong frequency peaks with harmonics in the envelope spectrum of the vibration signal. In the paper, we proposed a new type of indicator and compared it with the often used the log ratio of fault amplitudes. This relative value of characteristic fault frequencies works very effectively in the case of only one type of faults. In the case of simultaneous occurrence of several faults, this indicator often fails. We proposed a robust frequency indicator that correctly detects characteristic fault frequencies in such a situation. The conducted experiment in which we simulated the inner and outer faults race of a rolling bearing confirmed the effectiveness of the proposed indicator and its better identification properties in relation to the used logarithmic amplitude factor.

INTRODUCTION

Rolling Element Bearings (REBs) are among the most commonly used elements in machines, and their failure is one of the most common causes of machine failures and downtime. They are used in engines, vehicle systems, gas turbines, pumps and many other machines. The need to prevent these failures has initiated many studies on REB diagnostics based on vibration signals over the last few decades. This area is now quite well understood, thanks to the availability of many effective diagnostic methods. Typical rolling bearing failures include corrosion of the inner race, outer race and rolling elements, fatigue pitting and cage damage. Impulsive shock is generated by exciting high-frequency resonances of the bearing system structure when a rolling element failure hits the inner or outer race or rolling elements hit a failure of the outer or inner race. The periodicity and amplitude of shocks depend on many factors, including: shaft angular speed, bearing geometry (pitch diameter and rolling element diameter) and type of bearing load and damage location. The characteristic bearing fault frequencies can be divided into BPFI (Ball Pass Frequency on Inner Race), BPFO (Ball Pass Frequency on Outer Race), BSF (Ball Spin Frequency) and FTF (Fundamental Train Frequency). Equations (1 - 4) can be used to calculate this fault frequency for a stationary outer race as follows:

Ballpass frequency on outer race:

$$BPFO = \frac{nf_r}{2} \left(1 - \frac{d}{D} \cos \theta\right) = BPFO_{multiplier} \cdot f_r$$

Ballpass frequency on inner race:

$$BPFI = \frac{nf_r}{2} \left(1 + \frac{d}{D} \cos \theta\right) = BPFI_{multiplier} \cdot f_r$$

Fundamental train frequency (cage speed):

$$FTF = \frac{f_r}{2} \left(1 - \frac{d}{D} \cos \theta\right) = FTF_{multiplier} \cdot f_r$$

Ball spin frequency:

$$BSF = \frac{D}{2d} \left(1 - \left(\frac{d}{D} \cos \theta\right)^2\right)$$

where: [Hz] is the shaft rotation frequency, n is the number of rolling elements, is a pitch diameter, is rolling element diameter and is the contact angle. , and are the Fault Frequency Multipliers and are defined by the following equations:

$$BPFO_{multiplier} = \frac{n}{2} \left(1 - \frac{d}{D} \cos \theta\right)$$

$$BPFI_{multiplier} = \frac{n}{2} \left(1 + \frac{d}{D} \cos \theta\right)$$

$$FTF_{multiplier} = \frac{1}{2} \left(1 - \frac{d}{D} \cos \theta\right)$$

Note that the BSF is the frequency with which the fault strikes the same race (inner or outer), so that in general there are two shocks per basic period. Thus the even harmonics of BSF are often dominant, in particular in envelope spectra. Vibration diagnostics of rolling bearings is the identification of characteristic fault frequencies. In order to effectively identify the failure, it is necessary to create an appropriate indicator, the value of which would determine the occurrence or non-occurrence of a given type of fault. A popular indicator for identifying failures of the inner and outer race of the bearing is the relative value of the BPFI amplitude and the BPFO amplitude, often called the Log Ratio of Fault Amplitudes (LRFA). This indicator effectively identifies faults (BPFI and BPFO) occurring in a bearing individually. In the case of both types of faults occurring simultaneously, this indicator often fails.

EXPERIMENT

The available main methods to diagnose and examine rolling element bearings faults using vibration analysis are :

- Time domain methods
- Frequency domain methods
- Envelope analysis
- Time-frequency methods
- Cyclostationary analysis

This basic methods of vibration signal analysis presented above, apart from the first method, all of them are based on various forms of spectral analysis and the diagnostics itself is based on the detection (identification) of spectral lines related to a given fault. In older solutions, identification was carried out by simple visual inspection of the vibration signal spectrum. In automatic systems, in order to identify characteristic features of faults, there is a need to determine an appropriate indicator, the value of which would determine the occurrence of the fault. In the case of rolling bearing faults in the form of an inner or outer race defect, the relative value of characteristic frequency amplitudes of BPFI and BPFO, i.e. LRFA, is often used defined as

$$LRFA = \log \left(\frac{BPFI_{Amplitude}}{BPFO_{Amplitude}} \right)$$

Identification of a bearing inner race or outer race fault is performed by assigning appropriate ranges of this indicator values to faults of a given type. This indicator enables identification of three bearing conditions: inner race fault, outer race fault and no faults of this type. Appropriate clustering of the indicator is performed through a kind of training in which test signals from simulations of individual bearing conditions appropriately divide the applicable range of this indicator values. Based on the experiment conducted in, the authors provide a very simple classifier based on the LRFA indicator:

LRFA ≤ -1.5 - the bearing has an outer race fault
-1.5 < LRFA ≤ 0.5 - the bearing has no faults
LRFA > 0.5 - the bearing has an inner race fault

However, this simple classifier works well when only one type of fault occurs. Figure 1 shows the result of the envelope analysis of the vibration signal containing features of the bearing's outer race fault. The characteristic frequencies of BPFO and BPFI faults are marked with vertical lines. As can be seen, in this case only a characteristic frequency peak corresponding to BPFO occurred and the LRFA indicator was approximately -2.5. The above-presented classifier correctly identified the type of fault. Figure 2, on the other hand, shows the envelope spectrum of the signal from a bearing with an inner race fault.

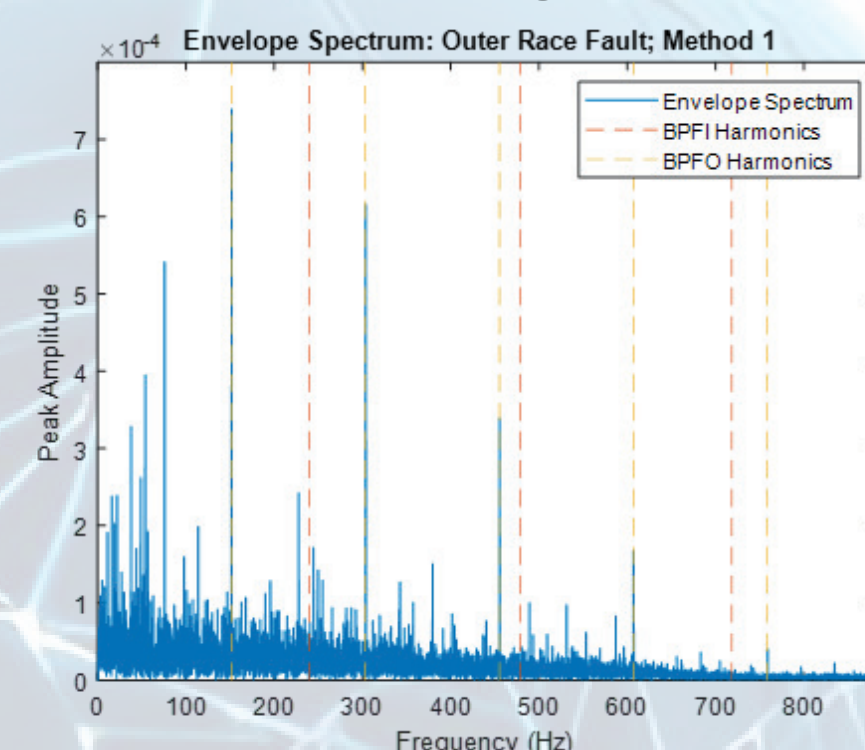


Fig. 1. Envelope spectrum of vibration signal containing features of the bearing's outer race fault. LRFA indicator was approximately -2.5.

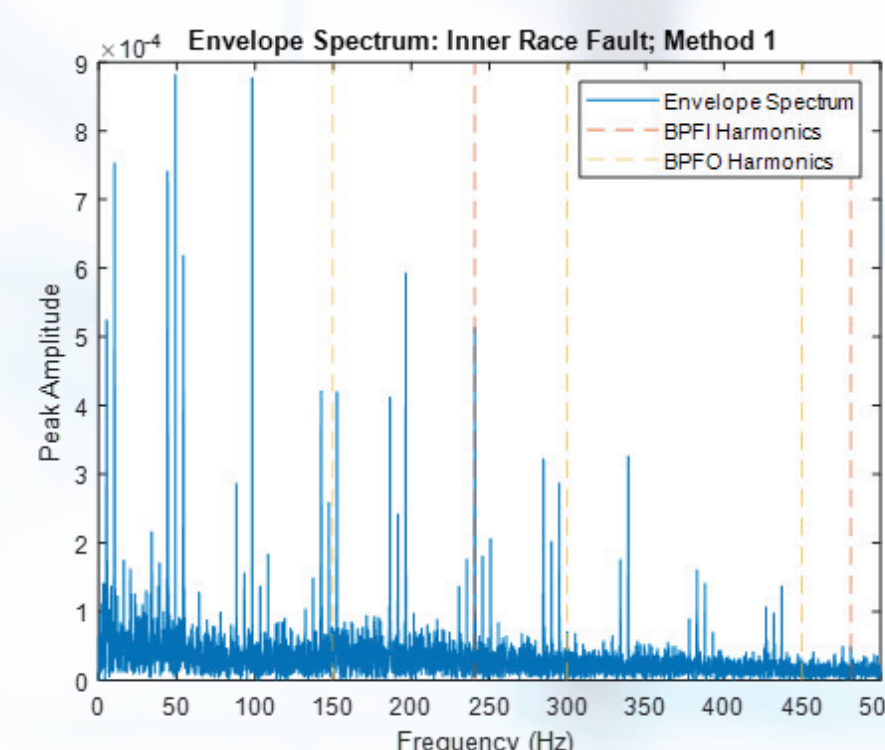


Fig. 2. Envelope spectrum of vibration signal containing features of the bearing's inner race fault. LRFA indicator was approximately 1.8.

The frequency peak corresponding to BPFI is clearly visible. In this case, the LRFA indicator has a value of approximately 1.8 and is within the range of inner raceway faults of the classifier defined above. In this case, too, the fault was correctly identified.

The problem with using the LRFA indicator occurs when both types of faults occur simultaneously. Figure 3 shows the measured vibration signal from a bearing with both inner and outer race faults. As can be seen, the envelope spectrum showed frequency peaks corresponding to both BPFI and BPFO. In this case, the LRFA indicator had a value of about -0.2, which the classifier based on this indicator identified as no fault. As can be seen, in this case, this indicator is not effective.

Experimental Results

In this chapter, we present the results of an experiment involving the identification of simulated bearing faults using the proposed NAFF indicator and compare them with the results obtained using the LRFA indicator. The measurement station is shown in Figure 6. The station consists of a rotating machine, a signal analyzer, and a set of vibration sensors. Outer and inner race fault of a rolling bearing was simulated in the rotating machine. Three triaxial vibration sensors placed on the bearing housings and located as shown in Figure 4 were used.

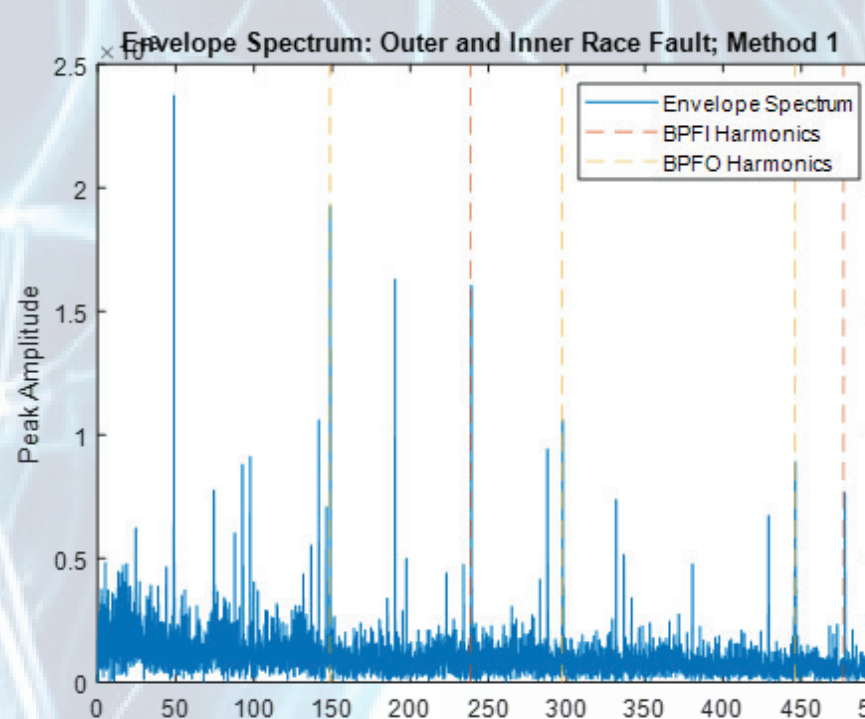


Fig. 3. The envelope spectrum of the vibration signal containing both features of the occurring faults. In this case LRFA indicator was approximately -0.2.

The measurements were carried out for a rotational speed of 3000 rpm. We simulated three types of rolling bearing faults, two single and one double:

- outer race fault,
- inner race fault,
- outer and inner race faults (simultaneously).

The precise measurement of the shaft rotational speed was =48.9Hz which allowed the calculation of the following characteristic damage frequencies:

BPFO = 151.74 Hz
BPFI = 239.51 Hz
FTF = 19.48 Hz
BSF = 97.41 Hz

During the experiment, a series of measurements of vibrations generated by the measuring station were made. Part of the measured signals was used as a training set to define a classifier based on the NAFF indicator. A simple classifier based on the NAFF indicator can be represented as:

NAFFs-6.5 the bearing has a fault of the type specified by FFA

This very simple classifier was tested on a set of test signals created from the remaining part of the measured vibration signals. The results of the correctness of the identification of the simulated faults are presented in Table 1. The values presented in the table are the percentage of correctly identified faults of a given type. For comparison, a similar analysis was performed for the classifier based on the LRFA indicator.

Table 1. Summary of fault classification results using the classifier based on the NAFF and LRFA indicators.			
	Inner race fault	Outer race fault	Inner and Outer race fault
NAFF	81%	87%	12%
LRFA	80%	90%	82%

As can be seen from the above results of the analysis of effectiveness in the case of single defects of the outer or inner race, the effectiveness of the tested classifiers was similar. In the case of the occurrence of both types of defects simultaneously, the effectiveness of the classifier based on the LRFA indicator was only 12%, in contrast to the classifier based on the proposed NAFF indicator, the effectiveness of which reached 82%. These results confirm the good identification properties of the proposed indicator.

CONCLUSION

The paper proposes a new effective and simple identification indicator for various types of rolling bearing faults. The theoretical part presents information on the basic rolling bearing faults. The frequencies associated with these faults are defined. The most commonly used diagnostic methods for rolling bearings based on the analysis of vibration signals are also presented. The proposed standardized fault identification indicator can be independently used to identify different types of faults simultaneously. In the conducted experiment, the effectiveness of a simple classifier based on the proposed NAFF indicator was assessed and the obtained results were compared with the classifier based on the LRFA indicator. The obtained results confirm the high effectiveness of the proposed indicator and its potential application in automatic systems for the diagnosis of rolling bearings.

METHODOLOGY FOR ASSESSING AIRCRAFT TIRE WEAR

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Keywords – Aircraft tires, tire wear, wear assessment methods, tire production technology, radial tires, diagonal tires, visual inspection, tire regeneration, tire durability, aviation safety.

ABSTRACT

The paper deals with methods of assessing the wear of aircraft tires. It focuses on the production technology, materials and factors influencing the operation of tires, such as pressure, landing speed and weather conditions. It discusses the development of tires from bias to radial, taking into account new materials such as Kevlar and synthetic rubber. The paper describes methods of assessing the wear, including visual inspections, laboratory tests and numerical analyses. It includes case studies of tire failures and the results of a survey on students' knowledge about their wear.

INTRODUCTION

Aircraft tires are a key element of the safety of air operations. The safety of take-offs, landings and maneuvering of aircraft at airports depends on their durability and reliability. During operation, tires are exposed to extremely difficult conditions, such as high speeds, rapid temperature changes, intense overloads and contact with the hard surface of runways. Therefore, their proper maintenance, regular assessment of technical condition and the use of modern production technologies are essential to ensure the safety of air operations. Technological progress in the field of materials and construction of aircraft tires, as well as the development of advanced diagnostic methods, have significantly improved their durability and resistance to wear. Modern tires are designed and manufactured using modern materials, such as Kevlar and synthetic rubber, which increases their resistance to mechanical damage and extreme working conditions.

SCOPE OF RESEARCH WORK

A. Methodology

The research focused on developing a comprehensive strategy for assessing aircraft tire wear, considering advancements in technology, design, materials, and operational conditions. It included a historical overview of tire construction, from bias ply to modern radial types, and examined the impact of innovations such as synthetic rubber and Kevlar on tire durability. The study analyzed both theoretical and practical aspects of tire wear, including the effects of landing speed, load, dynamic forces, temperature, and tire pressure. Common wear types such as tread wear, scuffing, and mechanical damage were described alongside tire production stages (forming, vulcanization, certification). Various assessment methods were explored: visual inspections, laboratory testing, and numerical simulations using the finite element method (FEM). Practical maintenance practices like correct storage and retreading were emphasized. The role of real time pressure monitoring systems (TPMS) in wear prevention was also addressed. The research incorporated case studies of tire failures and a survey evaluating the knowledge of aviation students and mechanics. Findings highlighted a need for practical training in tire wear assessment to improve safety and extend tire lifespan. The work proposed improvements for operational reliability in both civil and military aviation.

B. The importance of tires in the development of modern aviation

Aircraft tires have played a significant role in the development of modern aviation, influencing the safety and efficiency of flight operations. Modern tires are designed to withstand extreme conditions, including high G forces, sudden braking, high speeds, and sudden temperature changes. Their durability and reliability are crucial in the daily operation of aircraft, especially in the case of passenger aircraft that perform regular long distance flights. High strength and high performance tires have become one of the foundations of modern air travel, enabling safe and efficient operations at airports around the world.

C. Characteristics of aircraft tires

Aircraft tires are a key element of the safety of every aircraft, responsible for transferring forces during takeoff, landing, and movement on the airport runway. High durability, reliability and the ability to withstand extreme operating conditions are the features that tires used in modern aviation must meet. The construction of aircraft tires varies depending on their type, which determines their use and specificity of operation. Diagonal tires (Fig.1) are one of the basic types of aircraft tires, characterized by a simple but durable construction. In this type of tire, the cord layers are arranged alternately at an angle of less than 90 degrees to the tread axis. This construction provides them with high stiffness and mechanical strength. Diagonal tires were widely used in aviation from its beginnings until the development of radial tires, which are gradually replacing them in commercial and military aviation.

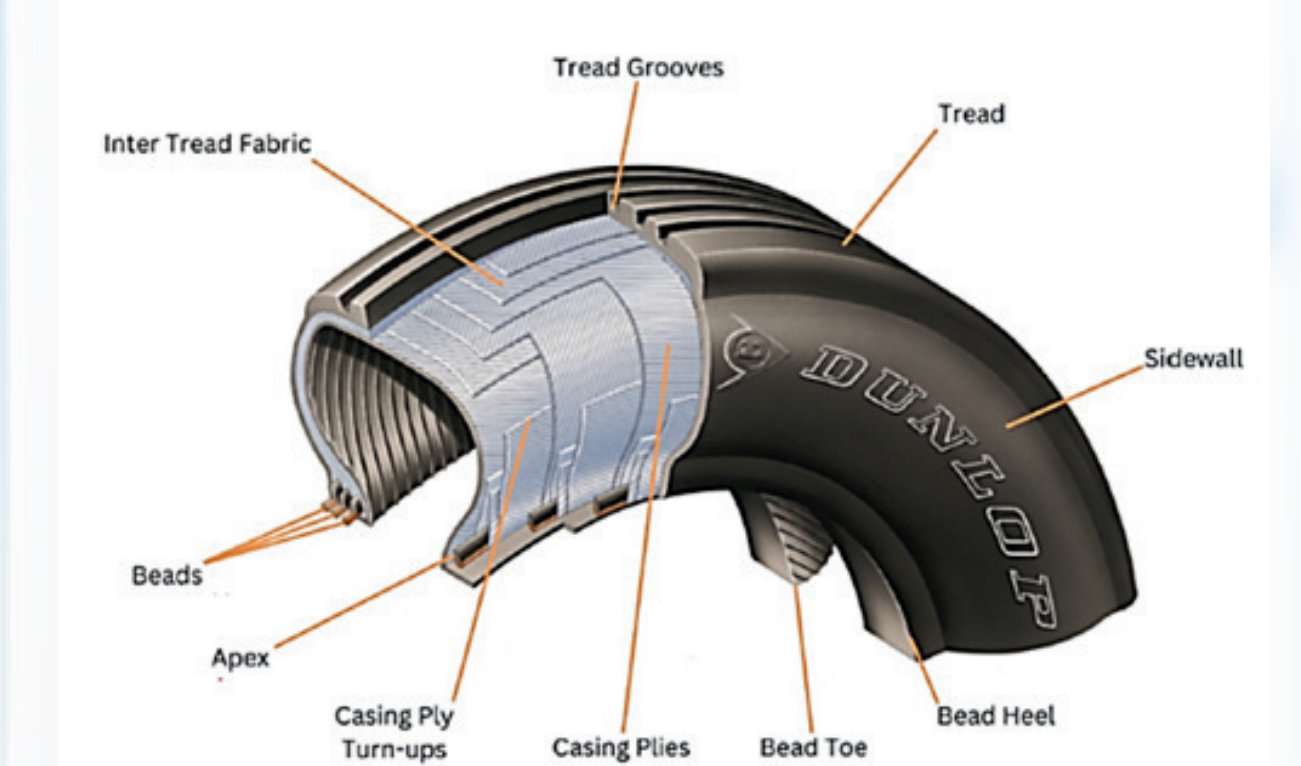


Fig. 1. Cross-section of a bias-ply tire and its components

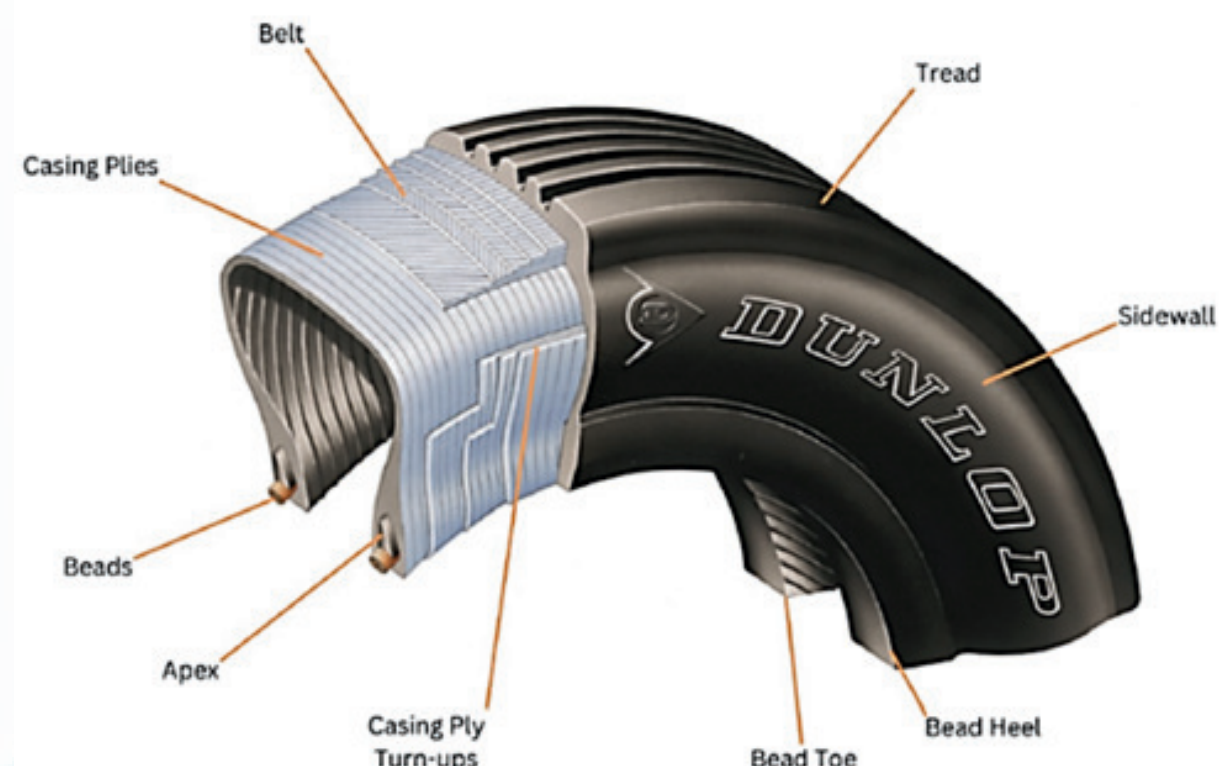


Fig. 2. Radial tire cross section and its components

Their main advantage is the ability to carry heavy loads while maintaining structural stability even at high speeds. However, a disadvantage is their limited flexibility, which can lead to faster wear when used frequently in extreme conditions, such as hard landings or emergency braking.

Radial tires (Fig. 2), introduced for aviation use in the second half of the 20th century, revolutionized the industry with their modern design. In radial tires, the cord layers are arranged perpendicular to the tread axis, which allows for a better distribution of forces acting on the tire during use. This design provides greater lateral flexibility, which allows for more effective absorption of shocks and vibrations, and also reduces material wear. In addition, radial tires use stabilizing belts that reinforce the tread, increasing the tire's resistance to lateral forces and providing better traction, which is crucial during takeoffs and landings on wet surfaces. Radial tires are lighter than bias ply tires, which contributes to reduced fuel consumption, which is important for large, heavy commercial aircraft. High fuel efficiency and longer tire life have made radial tires the dominant choice in modern aviation.

D. Materials Used in Aircraft Tire Manufacturing

Modern aircraft tires are made of steel wires, synthetic rubber and reinforcing fabrics such as nylon and Kevlar. Steel wires strengthen the bead area, enduring high forces during takeoff and landing. Synthetic rubber offers superior resistance to abrasion and heat compared to natural rubber, handling the intense friction and temperature changes during landing. Nylon and Kevlar reinforce the tire structure, with Kevlar providing high strength while keeping the tire lightweight.

E. Aircraft Tire Manufacturing and Certification Process

Aircraft tire manufacturing involves multiple stages, including material selection, layer formation, and vulcanization, using advanced technologies like CAD. Companies such as Goodyear and Dunlop conduct extensive durability, laboratory, and field tests to ensure tire performance under extreme conditions. Certification follows strict international standards (e.g., CAP533, CAP562) and is supervised by regulatory bodies like the FAA and EASA, ensuring the safety and reliability of aircraft tires.

TYPES OF DAMAGE AND WEAR OF AIRCRAFT TIRES

Aircraft tires are subject to a variety of wear and damage types due to the intense conditions in which they are used. The most common types of wear include:

- **tread wear**: a natural phenomenon resulting from tire use. The tread gradually wears away during landing and runway maneuvering, which may be accompanied by minor dents and tears. Excessive tread wear leads to reduced traction and can affect operational safety.
- **localized scuffing (scuffing)**: caused by heavy braking or skidding of the tires on the runway, especially when the wheels are not yet turning at the aircraft speed at the time of landing. Localized scuffing can lead to uneven tire wear and reduced tire life.
- **cuts and cracks**: caused by contact with foreign objects on the runway or with uneven surfaces. Cuts can lead to more serious tire damage, such as blowouts or loss of structural integrity.

Regular tire inspections are essential to detect damage early and prevent major failures. In addition, proper maintenance, including checking and maintaining proper tire pressure, significantly affects tires life and operational safety.

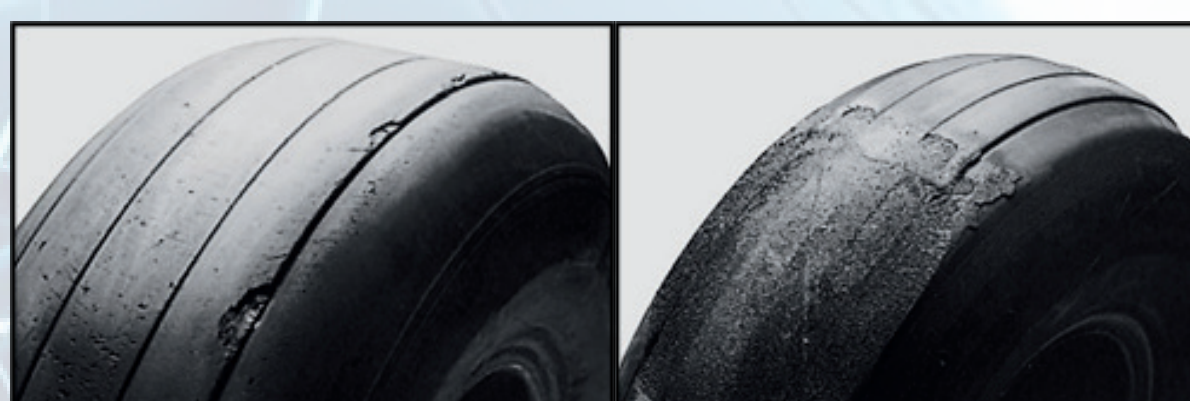


Fig. 3. Typical forms of wear during natural use of an aircraft tire: a) minor damage and tearing, b) flat abrasion of an aircraft tire caused by sudden wheel locking.

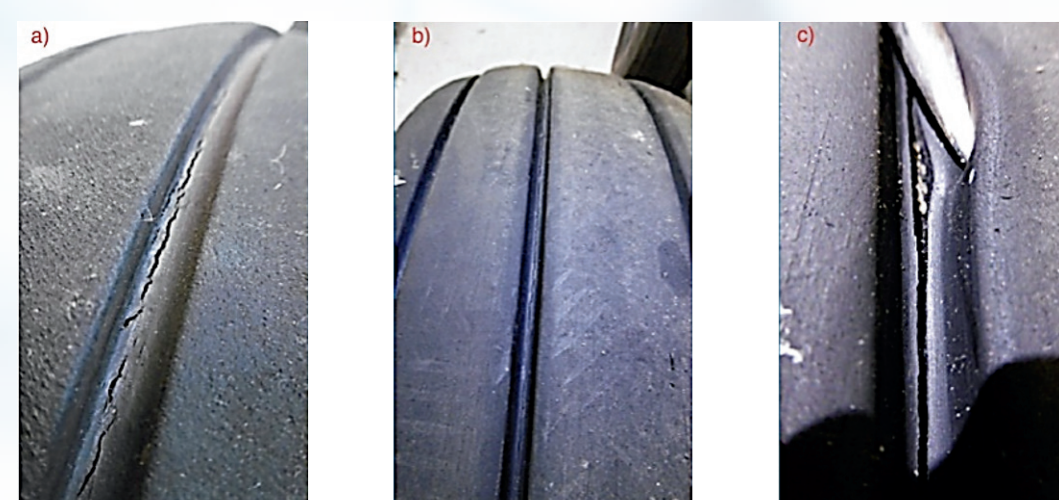


Fig. 4. Cuts and cracks in aircraft tires: a) crack on the sidewall of the groove, b) crack at the bottom of the groove, c) cut in the bottom of the groove.

The effect of tire pressure on tire durability has been widely documented in studies and maintenance manuals for aircraft tires. Too low or too high pressure can significantly affect the tire's service life and resistance to damage. Correct tire pressure is a key factor in ensuring that the tire maintains its load bearing and strength properties while minimizing the risk of abnormal wear. Low tire pressure leads to excessive tread deflection, which causes increased friction and generates higher temperatures during use.

Overheating the tire can lead to accelerated material wear and increase the risk of structural damage, such as cracks and cuts. On the other hand, too high pressure can reduce the tire's contact area with the ground, which can affect the stability of the aircraft during landing and take off, and also increase the risk of mechanical damage due to overloads. The recommendations for correct tire pressure are strictly controlled by manufacturers such as Goodyear and Dunlop, who emphasize in their instructions the need to check the pressure regularly, especially before take off. Studies show that maintaining optimal tire pressure can significantly extend the life of the tire and reduce the risk of failure during use.

FACTORS AFFECTING TIRE WEAR

Aircraft tire wear is influenced by multiple operational factors. High loads during takeoff, landing and taxiing increase pressure on tires, accelerating tread wear. Dynamic forces, like acceleration, braking and directional changes, particularly during landing when wheels experience slippage, also contribute to wear. Radial tires are often used as they distribute forces more effectively, improving durability.

A. Impact of Landing Wheel Speed

When aircraft wheels contact the runway, they accelerate from zero to match the aircraft's landing speed, causing slippage and generating heat that accelerates wear. Higher landing speeds lead to greater dynamic forces and faster tread wear, sometimes causing flat spotting. Radial tires, reinforced with materials like Kevlar, better withstand these stresses due to improved force distribution and optimized tread design.

B. Impact of Friction Forces During Contact with the Runway

Friction between the tire and runway causes heat buildup, leading to rubber degradation and increased wear. Heavier aircraft are particularly affected. Manufacturers address this by using heat-resistant rubber compounds and special tread designs that dissipate heat. Friction can also cause uneven wear, especially on wet or rough surfaces, which can be mitigated with optimized runway surfaces and anti-skid technologies.

C. Influence of Weather Conditions on Tire Wear

Temperature and humidity significantly affect tire wear. High temperatures soften rubber, increasing friction and wear, while low temperatures harden it, risking cracks. Advanced rubber compounds and cooling tread channels help manage heat. Humidity increases aquaplaning risk, requiring optimized tread designs for effective water drainage. Radial tires, with their better heat dissipation and structural strength, perform more reliably under variable weather conditions.

METHODS FOR ASSESSING THE WEAR OF AIRCRAFT

Aircraft tires are regularly assessed to ensure safety. Visual inspection, performed by trained personnel, detects damage such as cuts, cracks, deformations, or uneven tread wear, which may indicate issues with load distribution or landing gear alignment. Laboratory tests, including dynamometric tests and material wear analysis, evaluate tire durability under simulated conditions and material degradation. Mathematical models predict tire wear based on operational factors like speed and pressure, while simulation models analyze tire dynamics during takeoff and landing. Numerical methods such as Finite Element Method (FEM) provide detailed insights into stress, deformation, and performance under extreme conditions.

PRACTICAL OF AIRCRAFT TIRE MAINTENANCE

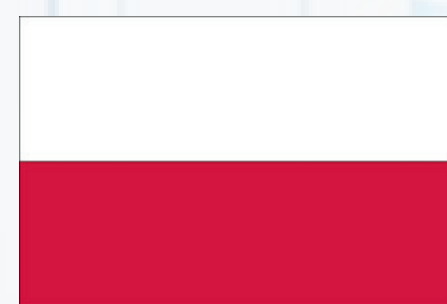
Proper storage and maintenance extend tire lifespan and reduce failure risks. Tires must be stored in cool, dry, and UV-protected environments, following manufacturer guidelines. Incomplete storage conditions, such as exposure to high temperatures or improper positioning, can lead to premature aging, deformation, and reduced performance. Regular monitoring of storage conditions ensures tire integrity.

TIRE REGENERATION TECHNIQUES

Retreading extends the service life of radial aircraft tires by replacing worn tread while preserving the tire casing. The process involves strict inspections for internal damage and uses advanced technologies like computer-controlled vulcanization to ensure safety and quality. Retreading reduces operational costs while maintaining safety standards; however, tires that fail inspection cannot be retreaded.

CONCLUSION

Aircraft tires are a key element of the safety of every aircraft. The paper is of a review nature, summarizing the current state of knowledge on a given topic. The work is a substantive guide to the methodology for assessing aircraft tire wear. By design, it presents the characteristics of aircraft tires from the moment of their production through operation until their final wear. The most common types of wear aircraft tires include: tread wear (excessive tread wear leads to reduced traction and can affect operational safety), localized scuffing (localized scuffing can lead to uneven tire wear and reduced tire life), cuts and cracks (cuts can lead to more serious tire damage, such as blowouts or loss of structural integrity). Friction forces that arise when a tire touches the runway are one of the most important factors influencing aircraft tire wear. Proper maintenance of aircraft tires is crucial for their durability and to ensure the safety of flight operations. Too low or too high pressure can significantly affect the tire's service life and resistance to damage. The materials used in aircraft tire manufacturing must be characterized by high strength, resistance to changing weather conditions, extreme temperatures, and high dynamic loads. The results of material analysis provide information on the durability of tires over a longer period of time and help predict when the tire should be replaced. UV radiation can cause micro-cracks on the tire surface. Proper management of storage conditions can significantly extend the life of aircraft tires by minimizing the impact of external factors on the aging process of the material. Thanks to retreading, the life of a tire can be extended even several times, which contributes to a more sustainable use of resources and reduced operating costs in commercial and military aviation.



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