Bearing Defect Simulation Library
Project Checkpoint

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1 Introduction

Bearing defect simulation is crucial when it comes to testing new defect detection methods. As explained in this project's proposal, current simulation technics either represent a localized defect or are limited to the fault with a simple geometrical shape. Thus, they do not enable the representation of complex defects. The current project attempts to address those limitations by developing a Library for bearing defect simulation where the user can specify complex defect shapes using a queuing model. As the simulation results need to be validated, it is also proposed to implement a simple model to calculate the localized faults' bearing defect frequencies.

This mid-point report is organized as follows; part II present the system under investigation, the conceptual models, as the calculation of the bearing defect frequencies. Part III describes the project's current status, the Verification of the conceptual models, the simulation models and program as they are for the moment, and a plan to validate the model. In part IV, there is a link to the Github repository of the project.

2 Description of the project

2.1 Bearing

Rolling element bearings are composed of 4 parts: an inner race, an outer race, some rolling elements (balls or rollers), and a cage that holds the rolling elements apart from one another. Figure 1 presents those different parts in a rolling element bearing.

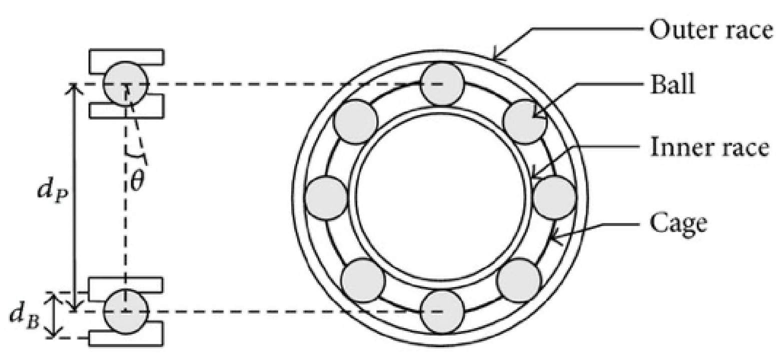
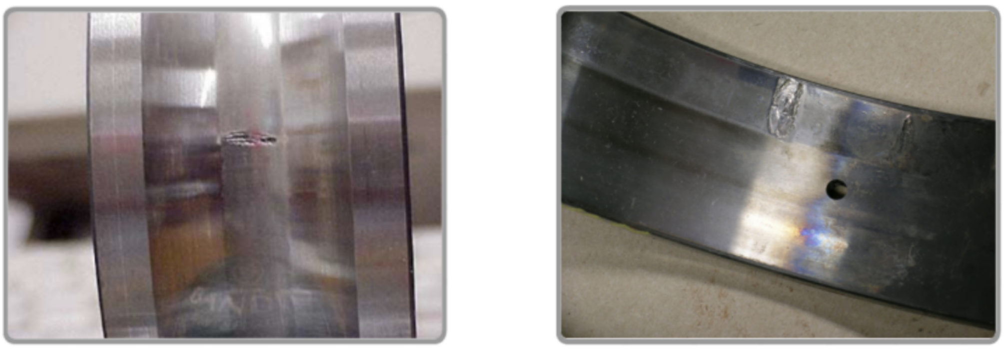


Figure 1: Components of rolling elements bearings[6]

2.2 Bearing defects

Any part of the bearing can wear out and eventually crack; the most common defects are located on the race as they are the most solicited components. Figure 2 [1] shows a defect on the outer race and a defect on the inner race. The passage of the rolling element on the defects generates an impulse that can be identified in the vibration signal.



(a) Inner-race fault (b) Outer-race fault

Figure 2: Race defects.

2.3 Bearing defect simulation

The simplest way to simulate bearing defect is to calculate the theoretical passage frequency of any rolling element on a given point of a race [4]. These frequencies formula only depend on the rotation speed of the bearing and its geometric configuration. This signal is then mixed with some noise to create a waveform[7]. More advanced methods consider the passage frequency and consider the defect's geometrical shape to obtain a more realistic waveform. In [8] where the shaft running the bearing is considered as a 2D beam and the rest of the bearing is modeled using a FEM model and Hertzian contact Theory [3]. In [2], the entire system is modeled using FEM, the results obtain are very precise, but it is often time complicated to have all the input required to feed such a model. However, there is very little work on more complex bearing defect shapes. Additionally, there is no open-source library to model bearing defects.

2.4 Conceptual Models

This part presents the conceptual models for the simple localized fault and the queuing model.

2.4.1 Simple localized fault

It is proposed to establish the equation for the frequency at which a the localized defect will excite the structure. In this case, we consider the bearing races and ball to be undeformable solid. We assume to know the the fundamental characteristics of the bearing:

- The number of balls n.
- The diameter of the ball d_B
- The pitch diameter, which is the diameter of the circle described by the center of the balls as they rotated around the bearing d_P.
- The contact angle θ, which is the angle between the plane of rotation of the races and the line that goes through a ball's contact point and the two races as shown in Figure 1.
- There is no slip between the balls and the races (the relative velocity between the ball and a race is zero at the contact point)
- The defect will be assumed to a be single "mathematical" point located on the outer or the inner race of the bearing.

2.4.2 Derivation of the bearing defect frequencies

From Figure 1, the radius of the outer race is given by $\frac{d_b}{2} + \frac{d_B}{2}\cos\theta$.Denoting N_o the outer race's angular speed, the velocity of a point of the outer race is:

$$V_o = \frac{N_o}{2}\left[d_P + d_B\cos\theta\right] \tag{1}$$

The velocity in the inner can be derived similarly to equation 1 and is:

$$V_i = \frac{N_i}{2}\left[d_P - d_B\cos\theta\right] \tag{2}$$

And the velocity a the center of the rolling element can be computer as the mean between the between V_i and V_o such that $V_c = \frac{V_o+V_i}{2}$. Then we can obtain the rotational speed at the center of the rolling element with:

$$\begin{aligned} N_c &= \frac{V_o + V_i}{2} \frac{2}{d_P} \\ &= \frac{1}{2d_P} \left[N_o \left(d_P + d_B \cos\theta \right) + N_i \left(d_P - d_B \cos\theta \right) \right] \\ &= \frac{1}{2} \left[N_o \left(1 + \frac{d_B}{d_P} \cos\theta \right) + N_i \left(1 - \frac{d_B}{d_P} \cos\theta \right) \right] \end{aligned} \tag{3}$$

From the above computed rotationnal speed we can compute the frequency at which a single element passes at a given point of the outer race:

$$\begin{aligned} N_{o/b} &= N_o - N_c \\ &= N_o - \frac{1}{2} \left[N_o \left(1 + \frac{d_B}{d_P} \cos\theta \right) + N_i \left(1 - \frac{d_B}{d_P} \cos\theta \right) \right] \\ &= \frac{1}{2} \left(N_o - N_i \right) \left[1 - \frac{d_B}{d_P} \cos(\theta) \right] \end{aligned} \tag{4}$$

Considering that they are n rolling elements in the bearing, we obtain the frequency of any rolling element passing on one given point of the outer race:

$$N_{o/b}^n = \frac{n}{2} \left| N_o - N_i \right| \left[1 - \frac{d_B}{d_P} \cos(\theta) \right] \tag{5}$$

Similarly to 5, we derive the passage frequncy of any rolling element on the inner-race:

$$N_{i/b}^n = \frac{n}{2} \left| N_i - N_o \right| \left[1 + \frac{d_B}{d_P} \cos(\theta) \right] \tag{6}$$

2.4.3 Summary of the bearing defect frequencies

Finally, we have obtained the excitation frequency for defects on the inner and outer-races, those frequency are called:

BPFO for Ball Pass Frequency Outer-race:

$$\boxed{BPFO = \frac{n}{2} \left| N_o - N_i \right| \left[1 - \frac{d_B}{d_P} \cos(\theta) \right]} \tag{7}$$

BPFI for Ball Pass Frequency Inner-race:

$$\boxed{BPFI = \frac{n}{2} \left| N_i - N_o \right| \left[1 + \frac{d_B}{d_P} \cos(\theta) \right]} \tag{8}$$

With:

- n : the number of rolling elements in the bearing
- N_o : the rotational frequency of the outer-race
- N_i : the rotational frequency of the inner-race
- d_B : the diameter of the rolling element
- d_P : the diameter of the circle discribed by the rolling element
- θ : the contact angle

Note: The equations derived above are present in almost any paper related to bearing defect, I am not pretending to have "discovered" it. However, in order to understand them a bit better I have done the derivations.

The next part presents the bearing defect with a more complex shape.

2.5 Queuing model for bearing defect

This model is the project's primary objective as we want to implement a library for complex bearing defect shapes. We will use a queuing model in which the bearing race on which the defect is located will be flattened and considered a half-space where balls are rolling. We assume that the problem is a plan and that we are looking at the plan where the ball is making contact with the defective race. We completely ignore the other race and assume that the load on the ball does not change.

Finally, we are making the following complementary assumptions:

- The defect is small enough such that there is only one ball in the defect region at the time.
- All the components of the bearing are undeformable.

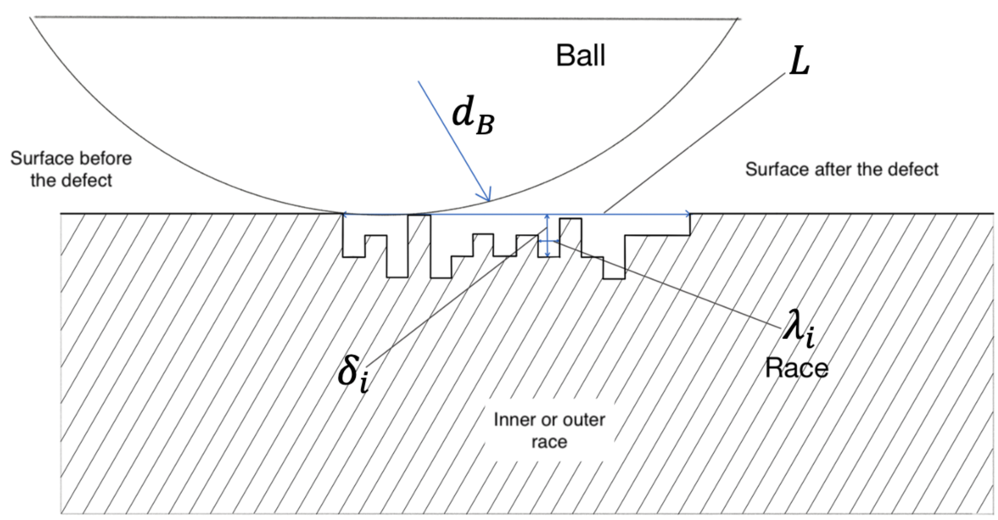


Figure 3: Modelisation of the defect.

A region of known size L contains the defect as presented in Figure 3, in which the ball is ""rolling" from left to right on the defect. This defect region is discretized into N intervals indexed from 0 to $N-1$, the length, and depth of interval i are respectively denoted λ_i and δ_i. The δ_i is positive when the material is missing on the race. We only consider positive depth even if, due to creeping [5], the race material could be higher than the race.

The process followed by each of the balls as it rolls on the race is as follows:

1. It starts by rolling on a region that is healthy and does not generate any vibration.
2. As soon as it enters the defect region, the ball starts to generate vibration every time it enters contact with a different interval. Hence, the simulation will first calculate which interval of the defect can enter the ball's contact; it will depend on its radius and the defect's specified geometry. For example, in Figure 3 some of the intervals cannot enter in contact with the ball as they are too deep. We will assume that the vibration's amplitude is directly related to the absolute value difference in depth between the two intervals on which the ball makes contact; that is, the higher the "step" is between the two intervals, the higher the vibration created will be.
3. Finally, when the ball exits the defect region, there is no vibration generated by the ball.

The different balls are equally spaced by a cage, as shown in figure 1. Thus, we assume the time interval between each ball to be equal to the ball frequency as calculated in equations 7 and 8 depending on if we model an inner race or an outer race defect.

Table 1 presents the different entities and attributes for the queing model.

Table 2 presents the constant and parameters of the queuing model. It should be noted that the parameters of the model all have the value *User set* as we are building a simulation library so the user can actively choose these values.

Table 3 present the activities for the queuing model.

Consumer: Set[n] : Ball	
Represents a ball rolling on the race of the bearing	
Attributes	Description
–	–
Queue: Unary: Waiting to go through defect	
Queue fo the balls that are waiting before going through the defect region	
Attributes	Description
REW	Number of rolling elements that still needs to go through the defect
Resource: Unary: Defect	
Represents the defect region where the balls are rolling	
Attributes	Description
DefectFree	Boolean: true if the next ball can enter the defect region

Table 1: Entities for the conceptual model.

Parameters		
Name	Role	Value
t_f	Left boundary of the observable time	User set
Ω	Revolution per minute of the saft	User set
L	Length of the defect region	User set
N	Number of intervals representing the defect	User set
λ_i	List of width of the N intervals	User set
δ_i	List of depth of the N intervals	User set
Constants		
Name	Role	Value
t_0	Right boundary of the observable time	0
n	Number of rolling elments	16
d_B	Diameter of the rolling elements	8.4074mm
d_P	Diameter of circle described by the rolling elements	71.501mm
θ	Contact angle	15.17°

Table 2: Parameters and Constants for the queing model

Activity: OnDefect	
Models a ball rolling in through the defect region	
Precondition	defectFree is True and there is still balls in the queue
Initiating Events	defectFree=False
Duration	$\frac{2L}{\pi d_P \pm \cos\theta} \cdot \frac{n}{\mathrm{BPFO/I}}$: the time spent by a ball in the defect zone
Terminating Event	REW-1; defectFree=True

Table 3: Activities for the queuing model.

2.6 Development plateform

As explained in the proposal the main goal of the project is to create a simulation tool for bearing defect. Thus, I will not use an interactive development plateform but create a C++ library that can be easily be used to generate bearing vibration signal.

3 Current state of the project

3.1 Verification of the conceptual models

As introduced in the proposal, the first model using calculating any rolling element's theoretical passage frequency on a given point of a race is a classical and straightforward model for simple bearing defect frequency. Thus, we will use the fact that this model is used in the literature as a verification.

3.1.1 Verification of the conceptual queuing model

As stated in the proposal, the defect generally occurs on the bearing's races, and we want to simulate complex bearing defect shapes. The conceptual model reduces the problem to multiple balls rolling on a track. The defect shape has been discretized and can represent a complex shape by setting different N intervals' depth and width representing the defect. Thus, the Conceptual Model for the queuing model correctly captures the various aspects of a bearing defect located on the inner or outer race.

Note: The Conceptual Model does not let the user specify multiple defects. Thus the model can simulate only one fault at a time.

3.2 Simulation model and simulation program

3.2.1 World view for the simulation model and program

The conceptual model will be translated into a Process-oriented model. I will consider the n different balls of the bearing as a different process using multi-threading. Considering that the number of balls in a bearing is limited and rarely more than 100, there should not be any issues with the number of threads.

The ball will be wrapped inside a bearing class presented in 4.

Class: Bearing		
Represent a rolling element bearing		
Attributes	Type	Description
m_n	int	Number of rolling elements of the bearing
m_dP	float	Pitch Diameter of the bearing (mm)
m_innerRace	bollean	True if we are studying the inner race
m_outerRace	bollean	True if we are studying the outer race
m_rpm	int	Rotational speed outer race vs inner race (rev/min)
m_ballList	array[n]	Array containing the balls objects
m_defect	defect	defect object
m_theta	float	contact angle (rad)

Table 4: Attributes of the class bearing

The ball object will be wrapped in a class Rolling Element as presented in the Table 5

Class : RollingElement		
Attributes	Type	Description
m_dB	float	Diameter of the ball (mm)
m_duration	float	Duration spent by the ball in the defect

Table 5: Attributes of the class Rolling Element

Finally, the defect will be described with a Defect class presented in Table 6.

3.2.2 Verification of the simulation program

As suggested by Professor Vuduk during the lectures, the code will be commented to show what aspect of the model is implemented in each function.

Class : Defect		
Attributes	Type	Description
m_L	float	Length of the defect (mm)
N	int	Number of intervals in the defect
m_lambda	array[N]	Array of N float representing the width of the intervals in mm
m_delta	array[N]	Array of N float representing the depth of the intervals in mm

Table 6: Attributes of the class defect

3.3 Plan for validation of the model

It is proposed to use face, behavior, and replicative validation on the waveform and the spectrum of both models' vibration signals to validate the model.

Face validation: Subject Matter Experts (SME)will be asked to check the signal to tell if it "looks right!"

Behavior validation: We will increase the bearing's rotational speed to validate that an increase of rotational speed leads to a rise in both models' defect frequencies.

Replicative validation: The NASA bearing defect dataset will be used for replicative validation. The test parameters will be fed into the simulation and the obtained spectrum will be compared to the spectrum of the NASA signals.

Comparison of the two models: By taking the case where the defect simulated by the queuing model is composed of only one interval of infinitely small width, we will compare the signals generated by the two simulations. Indeed, a single infinitely small interval should give the same results as the simple localized fault model.

3.3.1 Revision of the project's proposal

The project proposal is amended to reduce it to a single defect per bearing. Indeed, the two conceptual models that we described here constitute more than enough work and more complex cases where defects on the inner race and the outer race are not considered, even if it is pretty standard. Also, the motor driving the bearing was not mentioned in the project description. Compared to the real-life case, there is often some shaft and a motor to create the bearing's rotation. Those elements generally create more vibration in the system, present in the data collected with accelerometers. However, the project will be restricted to the bearing vibration, and other external sources of vibration will be ignored.

3.4 Division of the work

I am doing everything.

4 Github Repository of the project

The project repository can be found at this address:
`https://github.gatech.edu/prauby3/Bearing_defect_simulation`.
The repository is private, and I have added all the Teaching assistants as collaborators to it.

References

[1] Mobius institute - rolling element bearings. Mobius institute website.

[2] D. Stronbergsson et al. Multi-body simulation and validations from rolling-element bearings. *Journal of Engineering Tribology*, 09 2020.

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