CASE STUDY: APPLICATION OF AFD – FAILURE ANALYSIS FOR THE ANALYSIS OF POWER TRANSFER BETWEEN A TRANSMISSION SUN GEAR AND ASSOCIATED SATELLITES

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-CASE STUDY ABSTRACT

Solving difficult problems is a complex activity that is governed by the search for knowledge. Problem solving is affected by a combination of the searching process and by the availability of the knowledge required to solve the problem. This paper describes the application of the Ideation/TRIZ Methodology and specific analytical and knowledge-base tools as used in a project to support the needs of Ford Motor Company to solve a complex technological problem.

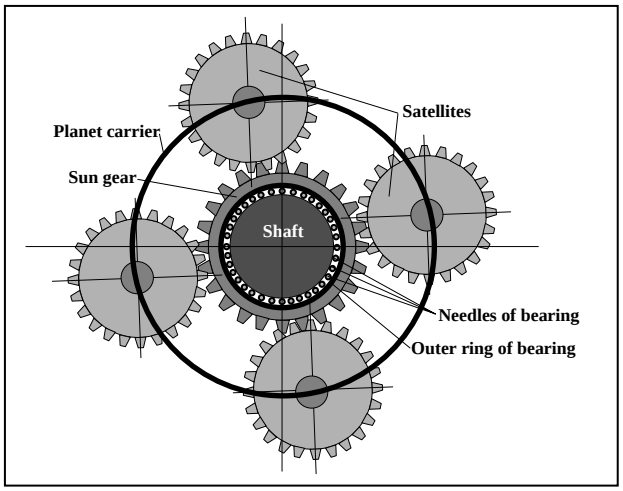
Automotive Industry – Warranty Problem

Warranty claims and recalls have a significant impact on the profitability of the automotive industry. Even the best engineers using highly respected methodologies such as Failure Mode Effects Analysis (FMEA), Design of Experiments (DOE) and business practices such as Six Sigma find it difficult and time consuming to use these tools and practices to solve some of their most challenging problems.

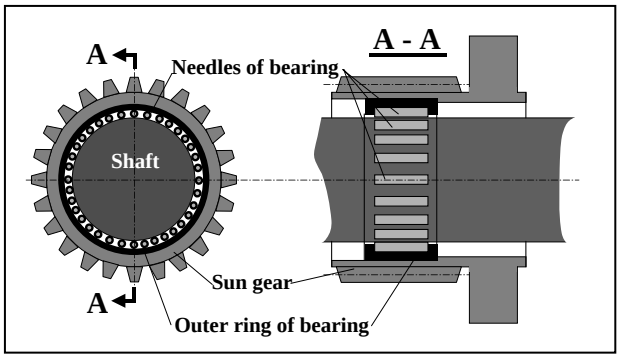
TECHNOLOGICAL PROBLEM STATEMENT

As a result of increasing engine power, an unexpected drawback related to a widely used, high quality transmission occurred. In some vehicles the bearing associated with the sun gear mechanism was walking out of the central bore. As a result of the undesired movement in the axial direction, the bearing was contacting other parts creating friction resulting in noises and destruction of the bearing and other parts.

Attempts were made to correct this situation by increasing the press fit into the sun gear bore. This effort resulted in increased bearing movement rather than eliminating it.



End View of the System Containing the Problem



Side View of System Containing the Problem

ANTICIPATORY FAILURE DETERMINATION™ (AFD) FOR FAILURE ANALYSIS

The AFD process for Failure Analysis is a systematic and structured process that is a practical application of I-TRIZ. Based on TRIZ, a Russian acronym for the Theory of Inventive Problem Solving, I-TRIZ is

the result of the extensive research and practical experience of the Kishinev School and Ideation International. AFD–Failure Analysis is a general purpose application that can be utilized in different areas of human activity such as, technology, business, and everyday life where there is a need for the following:

- To reveal the root cause(s) of an error, unsuccessful action, manufacturing failure or accident.
- To develop effective and simple approaches for eliminating the associated problems.
- To investigate the unclear mechanisms of any phenomenon or event.

In order to accomplish this goal, there is a conversion from inventing a solution to the problem to inventing the harmful conditions that created the problem. This is the foundation of AFD – Failure Analysis. It is based on the fact that in order for a failure to occur all of the factors (resources) must be present. If these factors cannot be readily seen, then existing resources are recombined to invent the harmful conditions, failure mode(s).

THE AFD–FAILURE ANALYSIS PROCESS AND ITS APPLICATION BY PROBLEM SOLVERS

Ideation TRIZ Specialists worked with Ford Subject Matter Experts (SMEs) to solve this technological problem in 1994. It was based on portions of the following current education/business model.

- Management commit~~men~~ment to training and solving the stated warranty-based technological problem
- Pre-training self-study of basic educational materials ~~'~~
- Self-Sufficiency the AFD–Failure Analysis program
- Utilization of the AFD–Failure Analysis System s~~S~~oftware
- Post-training mentoring of the team is provided over a period of 45 to 60 days (10 hours of contact time) by an Ideation TRIZ Specialist to insure the team's successful elimination of the problem*

** Post-training mentoring is an integral part of the educational process, and is not a consulting service. This support function is designed to provide new students of AFD–Failure Analysis with expert advice on how the methodology should be applied to ensure that they achieve their goal. Where required due to problem complexity, Ideation TRIZ Specialists work in parallel with student Subject Matter Experts (SMEs) to resolve the problem while the SMEs learn the process (In this case, the resolution of this technological problem had been pursued for over 2 years by a large team of engineers. The problem was resolved in parallel with basic education of the engineers and management.)*

Utilization of the AFD – Failure Analysis Process

The Failure Analysis begins with a questionnaire called the Failure Analysis Questionnaire (FAQ). The FAQ is a template for preliminary situation analysis, and consists of a set of questions that help define the problematic situation from a different point of view. These questions are not typical engineering- or management-oriented questions, but are oriented toward the discovery of the real problem and the mechanism causing the problem. The questions are the result of years of accumulated research in the successful application of AFD methods and related to the explanation of previously unsolved problems and their underlying failure mechanisms. The questions in the FAQ provide the practitioner with a systematic way to attack the system containing the failure prompting him/her to consider things that are typically disregarded or go unnoticed during problem solving.

The software-supported questionnaire contains two main topics that begin to define the problem and system where the problem resides:

1.1. Failure or drawback for which the root-causes are unknown

1.2. System where the failure occurs (including system name, system structure, primary useful function, useful functions, harmful effects)*

* This topic is supported by graphic modeling of the useful and harmful effects by the Problem Formulation portion of the AFD – Failure Analysis System software, which will be discussed in more detail in this paper.

Case Study Application of the Failure Analysis Questionnaire (FAQ)

Prior to the Self-Sufficiency in AFD–Failure Analysis training session, the Ssubject Mmatter Eexperts completed a detailed FAQ (not shown). This pre-workshop FAQ einsured that the defined problem wais suitable for Failure Analysis using the AFD–Failure Analysis™ System sSoftware, prepared the students for working on their problem and prepared the Ideation TRIZ Specialist for working on solving the problem in parallel.

The Ideation Process for Failure Analysis

Note: The following FAQ was abbreviated for purposes of this paper.

1. Failure Analysis Questionnaire

1.1. Failure or drawback for which the root cause(s) are unknown

As a result of increasing the engine power, an unexpected drawback related to an existing, well-established automobile transmission surfaced. In some vehicles the sun gear mechanism bearing was moving, walking out, of the central bore moving. During this movement in an axial direction, the bearing contacted other parts creating friction, which resulted in excessive noise and destruction of the bearing and other parts.

Attempts to correct the situation included increasing the bearing press fit into the sun gear bore unfortunately this had an unexpected impact, it increased the bearing movement instead of stopping it.

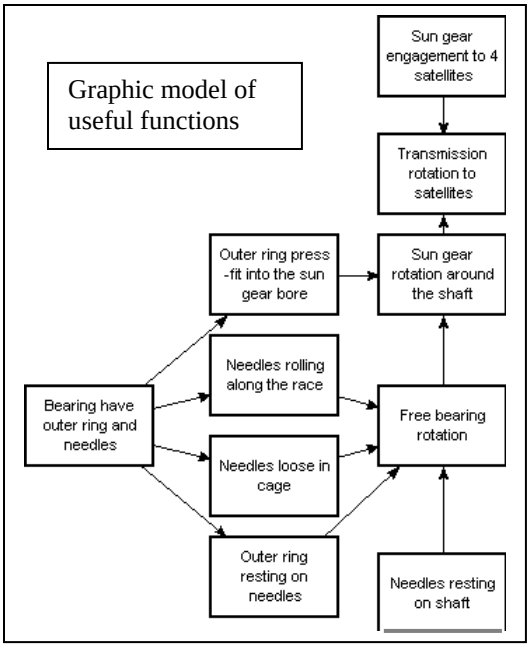
1.2. System where the failure occurs

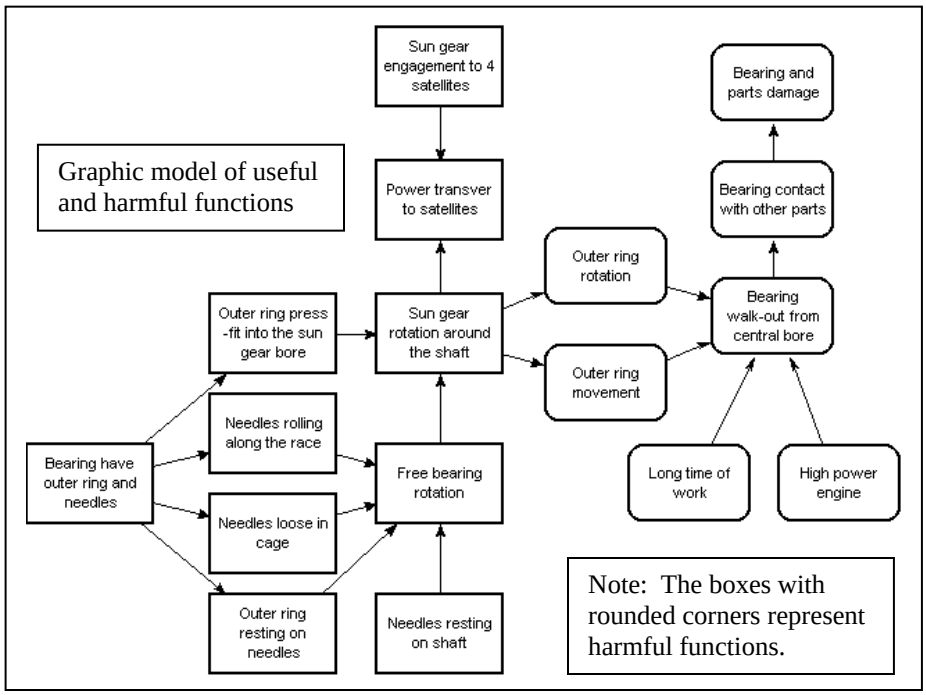
System name
Gear box

System structure
Helical sun gear
Shaft
Bearing needles
Four helical satellites
Bearing outer ring

Primary Useful Function
Power transfer between the sun gear and satellites

Useful functions
The useful functions are modeled in the graphic model below. The arrows in this diagram mean "produces", for example, sun gear engagement to 4 satellites 'produces' transmission of rotation to satellites. All of the boxes contain useful functions.





Harmful Functions
The graphic model on the previous page shows the addition of harmful functions to the graphic model of useful functions.

The development of graphic models such as those shown is done in a software-based tool called the Problem Formulator, which is an integral component of the AFD System software. This tool provides a means for graphically modeling the problem situation and for conducting a detailed analysis. The analysis is done through a patented algorithm that generates information required to tap into a knowledge base that supports the comprehensive development and elimination of failure modes.

2. Problem Formulation

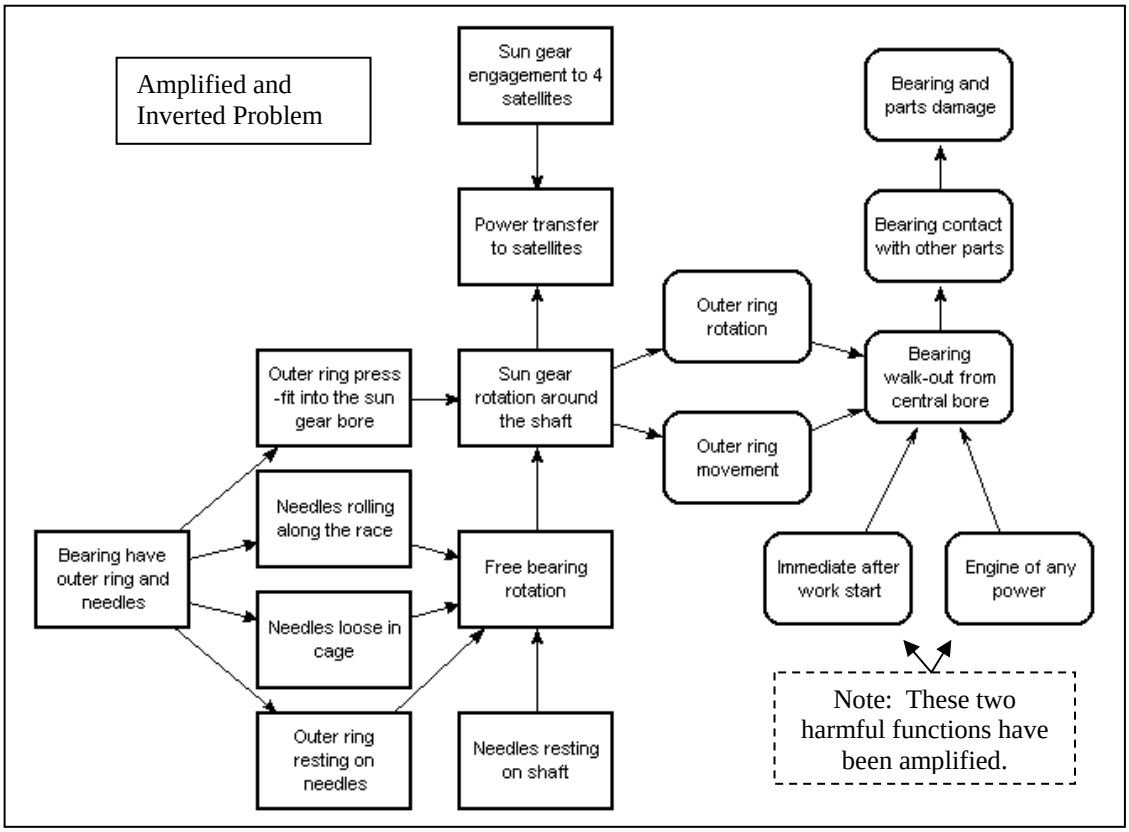
2.1. Localizing the failure (see diagram below)

Last Event(s)
Outer ring rotation
Outer ring movement

Conditions that initiate or accompany the failure
High power engine
Use over an extended period of time

2.2. Formulating the Inverted Problem (software generated problem inversion sets the stage for inventing the failure)

1) Find a way to provide [the] (Outer ring movement) with help of [the] (Sun gear rotation around the shaft), and any other function, which happens before the Last Event.
2) Find a way to provide [the] (Bearing walkout from central bore) with help of [the] (Outer ring movement), (Outer ring rotation), (Long time of work), and (High power engine), and any other function, which happens before the Last Event.
3) Find a way to provide [the] (Outer ring rotation) with help of [the] (Sun gear rotation around the shaft), and any other function, which happens before the Last Event.
4) Find a way to provide [the] (Bearing contact with other parts) with help of [the] (Bearing walkout from central bore), and any other function, which happens before



the Last Event.

5) Find a way to provide [the] (Bearing and parts damage) with help of [the] (Bearing contact with other parts), and any other function, which happens before the Last Event.

3. Providing Failure Hypotheses

3.1. Amplified and Inverted Problem

Bearing walkout from central bore occurs immediately after the sun gear starts moving and with engines of any power (see the graphic model on the previous page).

3.2. Generating Failure Hypotheses

This stage in the process consists of finding a way or method by which the Amplified Failure can be intentionally produced.

For this purpose:

1. The team reviewed those areas of engineering, science or everyday life where the phenomenon represented by the Amplified Failure is utilized for some useful purpose.
2. Next they considered the methods as hypotheses for the possible root cause(s) of the failure.
3. These hypotheses are then added to the graphic models.
4. The software knowledge base (Innovation Guide) supports the next step by providing information that is used to generate additional ideas about how to product and utilize technological effects.

Note there is a direct linkage between the graphic model and the software knowledge base that provides direct support for creating the desired harmful conditions, failure modes.

Example of Innovation Guide Knowledge Base

The knowledge base suggests to:
Create a desired field or action/impact
▼
Mechanical impact (is one of the suggested ways to do achieve this)
▼
Further refinement suggests considering – Mechanical impacts of solid-state objects
▼
Mechanical impacts can be obtained using the properties of solid-state objects, in particular:

- elasticity
- inertial or centrifugal forces
- friction

This sequence of associated information leads to the following thought process:

In order to create outer ring rotation and outer ring movement we need at least 2 forces:

- Tangential force to provide rotation
- Axial force for provide linear movement

Only one source of forces exists in the system, the sun gear's rotation around the shaft, so at this stage, an effort was made to invent a method that converts the sun gear rotation into tangential and axial forces. To provide movement, we should evaluate a mechanism, which somehow decreases the friction between the bore and the bearing. Known mechanisms of friction weakening are connected with:

- Vibration
- Surface lubrication

Next there was an analysis of existing resources that were available in the system and capable of providing the observed phenomena

The only source of forces in the system is the sun gear's rotation around the shaft. The objective at this point is to invent a method of converting sun gear rotation into tangential and axial forces. This process consisted of finding the resources and recombining them to create failure hypotheses.

1. Sources of vibration include:
   - Vehicle vibration from road irregularities
   - Vibrations transferred from the engine
   - Vibrations transferred from other parts of transmission
   - Vibrations generated directly in the sun gear mechanism
2. Resiliency (elasticity) of structural elements include:
   - Elasticity of the sun gear
   - Elasticity of the outer ring
   - Needles loose in cage
3. Possible weakening of friction between central bore in sun gear and outer ring

This information suggested a general idea, on the basis of which was generated hypotheses for mechanisms that could cause outer ring movement. It was quite obvious that this movement had something in common with the principle of transportation or movement via vibrational action. Most likely it was connected with several different mechanisms of "pseudo-vibrational motion", in particular:

- Friction influence on the interaction of outer ring and central bore in sun gear
- Friction influence on the needles
- Friction influence on the interaction between the needles and shaft.

The process of using software-based knowledge and illustrations to draw analogies, such as that presented above, resulted in the generation of knowledge related to the problem. The following is a set of key ideas that lead to the resolution of the problem.

- Vibration can decrease the friction between the outer ring and central bore
- Outer ring movement could be easily realized, if it could "float" in central bore.
- Additional influences on the outer bore movement could be realized that if there was be a thin layer of liquid between the surfaces of the bore and the outer ring. This implies that the phenomenon of wettability, lubrication, etc. may intensify sliding.
- Liquid may permeate into gaps between central bore surface and outer ring with extremely thin gap (or even no gap), especially under the condition of vibration.
- Liquid penetration into gap is possible due to capillary phenomena.
- Tremendous capillary forces ensure that it is likely for friction between central bore and outer ring to be weakened because of liquid penetration.

Development of Hypotheses

From the previous utilization and development of related knowledge, the team developed numerous hypotheses as follows:

Harmful effect hypothesis 1: Helical rotating wave

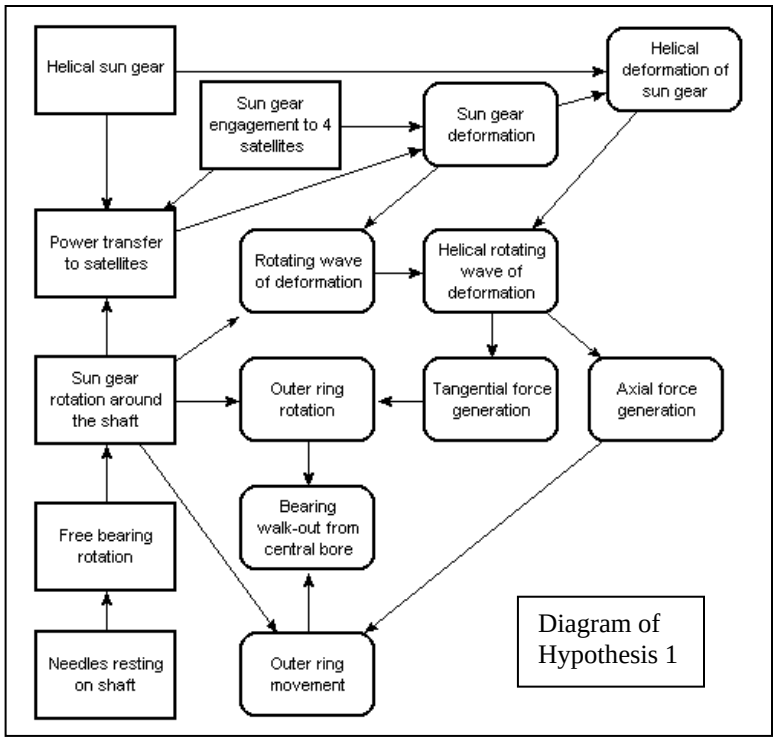
Text description of the conditions

- Sun gear rotation around the shaft
- Sun gear engagement to 4 satellites
- Power transfer to satellites
- Helical sun gear is utilized

Text description of the results

(Sun gear engagement to 4 satellites) together with (power transfer to satellites) causes a strong force acting on the sun gear from the satellites. This force generates a (rotating wave of deformation) of sun gear.

Each hypothesis was diagrammed (see the diagram below) so that the software knowledge base could be leveraged later to eliminate the failure mechanisms associated with the problems.



Harmful effect hypothesis 2: Spiral marks plus rotation

Text description of the conditions

- Sun gear rotation around the shaft
- High friction in bearing

- Outer ring press-fit into the sun gear bore
- Spiral mark on bore surface created by turning bore in sun gear

Text description of the results

(High friction in bearing) creates a (tangential force) which creates (outer ring rotation). (Outer ring rotation) together with (outer ring press-fit into the sun gear bore) and together with (spiral marks on bore surface) causes the creation of an axial force which causes (helical motion of the outer ring) and (bearing walk-out from central bore).

The team then defined this as a real process titled – "unscrewing" the outer ring from bore (see diagram below).

Harmful effect hypothesis 3: Skewing the needles

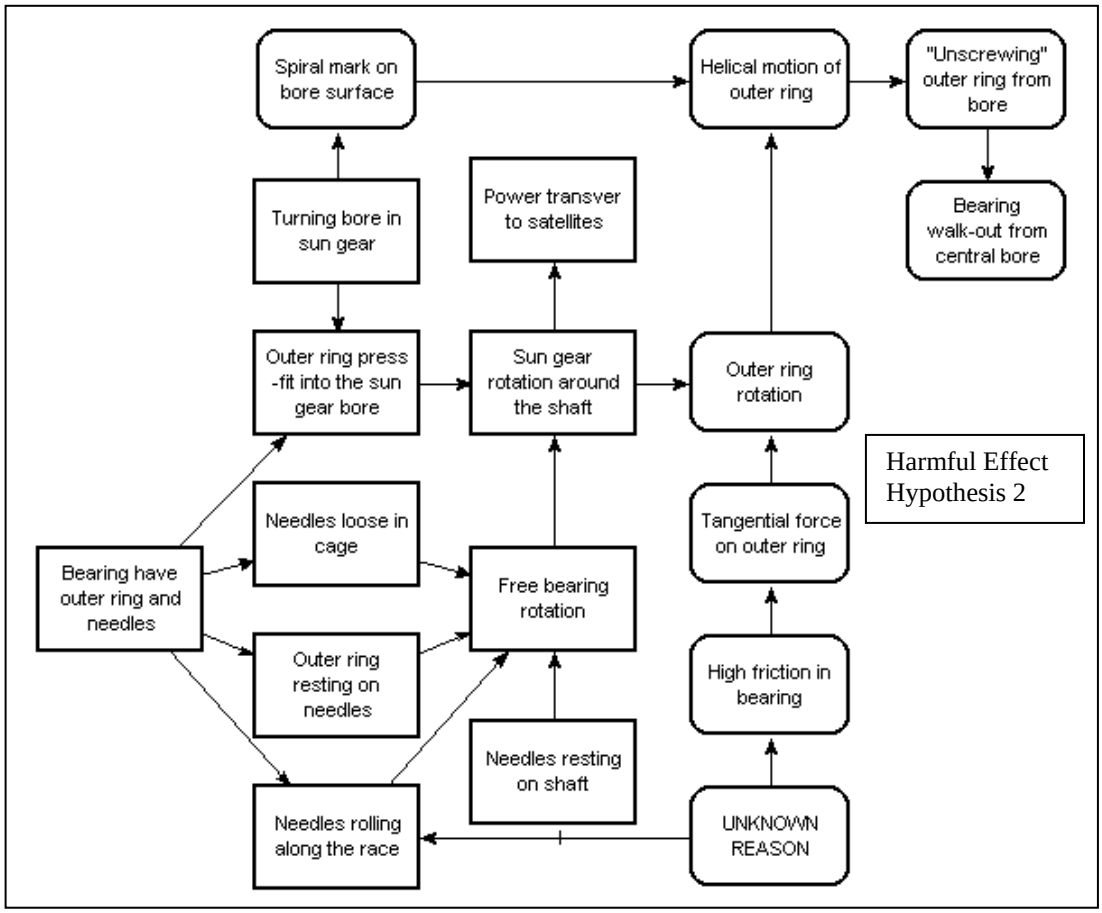
Text description of the conditions

- Sun gear rotation around the shaft
- Needles resting on shaft
- Power transfer to satellites
- Sun gear engagement to 4 satellites
- Outer ring resting on needles
- Needles rolling along the race
- Needles loose in cage

Text description of the results

(Helical deformation of sun gear –(see hypothesis 1) together with the (outer ring press-fit into the sun gear bore) creates (helical rotating deformation of outer ring). (Helical rotating deformation of the outer ring) together with (outer ring resting on the needles) and the (needles loose in the cage) creates (skewing of the needles). (Skewing of needles) together with (needles rolling along the race) and (needles resting on the shaft) create (tangential force generation), (generating of axial force on outer ring) and (increased friction at the bearing surface).

This was summarized as – increasing friction at the bearing surface is a realistic reason for "unscrewing" the outer ring from bore (See hypothesis 2).



Harmful effect hypothesis 4: Intensification of bearing movement

Text description of the conditions

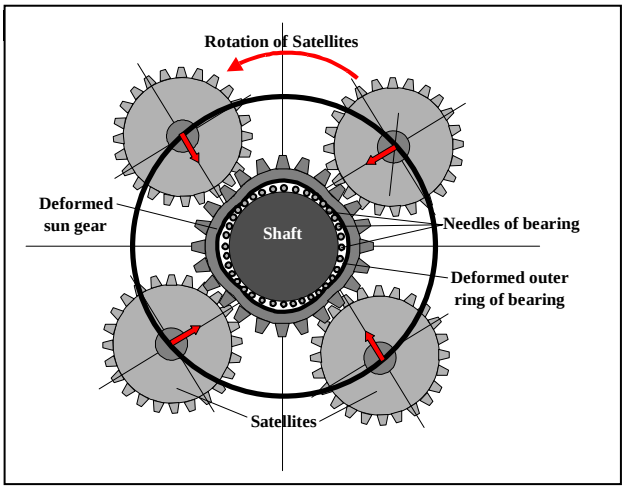
- Outer ring press-fit into the sun gear bore
- Rotating wave of sun gear deformation
- Spiral mark on bore surface
- Generation of vibration
- Transmission liquid around components

Text description of the results

(Outer ring press-fit into the sun gear bore) together with (spiral mark on bore surface) causes (capillary gap between bore and outer ring). (Capillary gap between bore and outer ring) together with (transmission liquid around components) causes (transmission liquid to go between bore and ring).

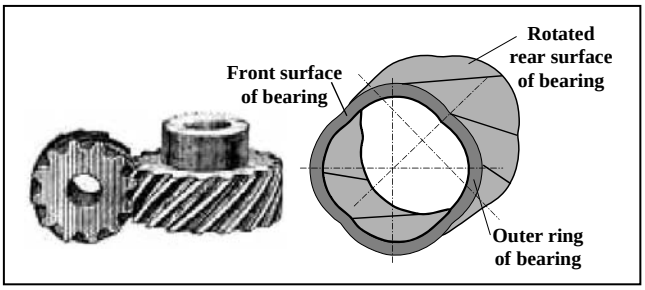
This process is increased by the (rotating wave of sun gear deformation) because this wave together with the (generation of vibration) creates the opening and closing of the gap.

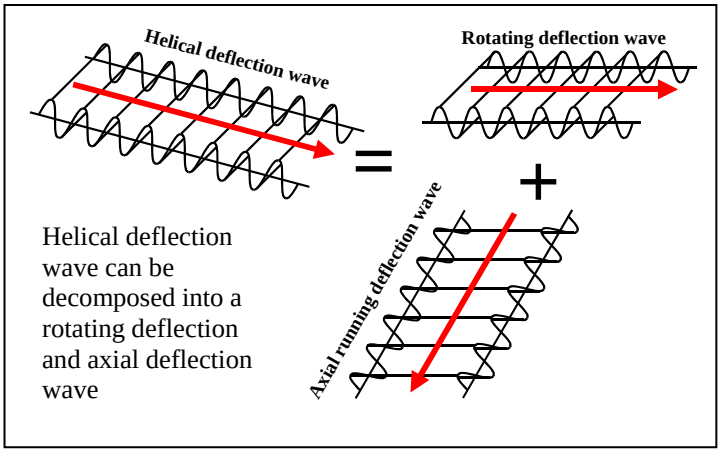
The team then defined this as "gap breathing" or "vibration pump" and restated the hypothesis as – (Transmission liquid goes between bore and ring) working as a lubricant, reducing friction between outer ring and central bore. This vibration reduces friction.



Graphic depiction of the hypothesis (see diagram above)

Deformation of the sun gear together with the helical sun gear causes helical deformation of sun gear (see the previous and next diagrams).





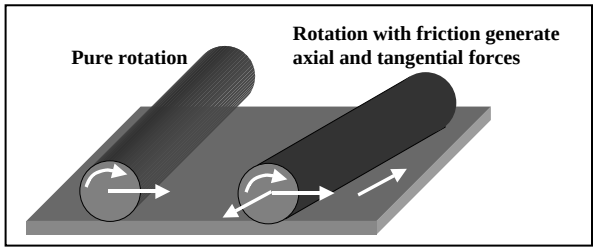
Helical deflection wave can be decomposed into a rotating deflection and axial deflection wave

Text description of the hypothesis:

(Helical deformation of sun gear) together with (Rotating wave of deformation) create (Helical rotating wave of deformation), this wave can be decomposed into two waves - tangential rotating wave and axial running wave.

Both waves create forces:

- Tangential rotating wave creates tangential force which creates outer ring rotation
- Axial running wave creates an axial force which creates outer ring axial movement
- Outer ring axial movement creates bearing walk-out from central bore



Helical deformation of sun gear (hypothesis 1) together with outer ring press-fit into the sun gear bore creates helical rotating deformation of outer ring. Helical rotating deformation of outer ring together with outer ring resting on the needles and needles loose in the cage creates skewing of needles. Skewing of needles together with needles rolling along the race and needles resting on shaft creates the generation of tangential force generation, generating of axial force on the outer ring and increasing friction between the bore and bearing.

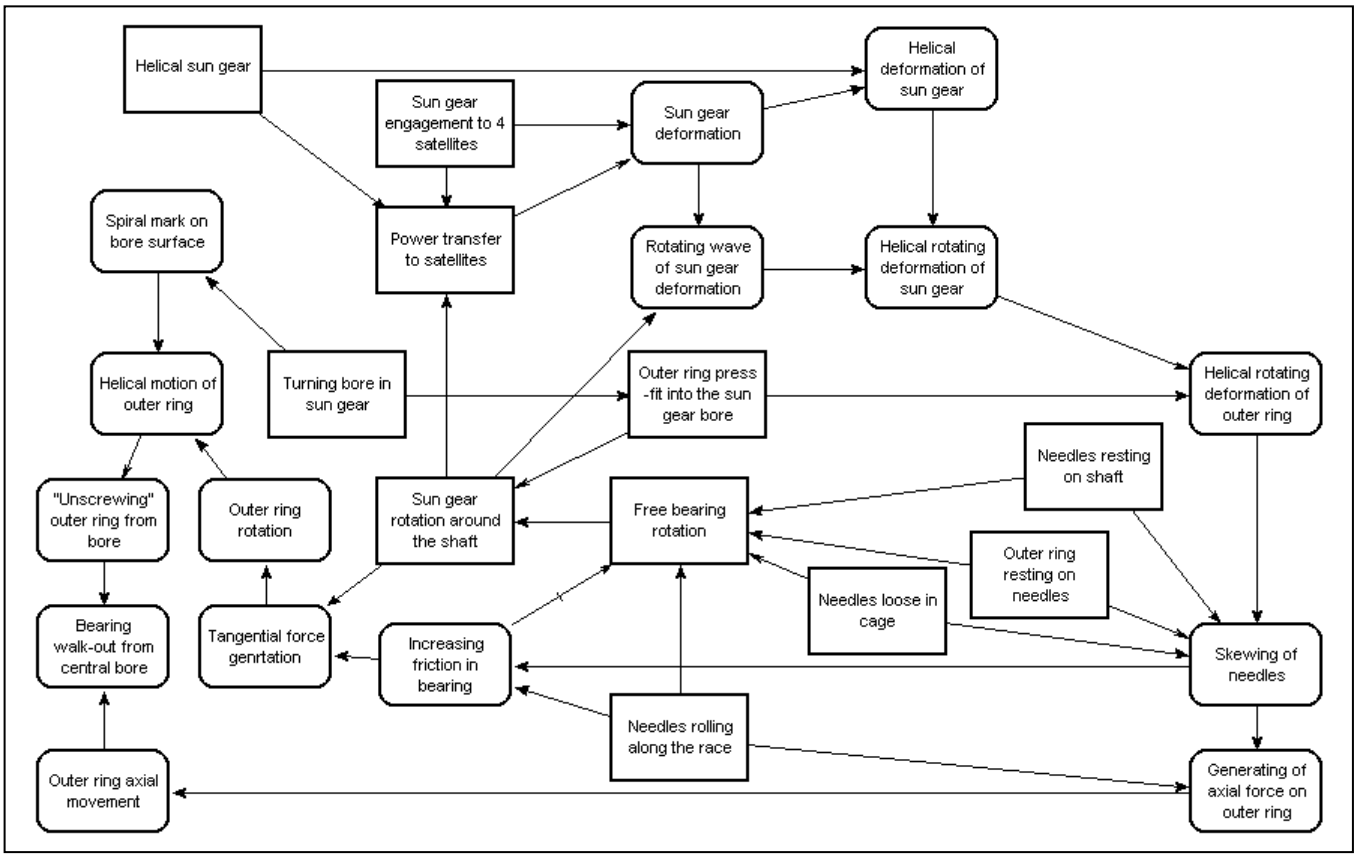
As knowledge was acquired additional graphic models were developed for all hypotheses these diagrams provide access to the extensive software knowledge base, which is designed to support the elimination of identified failures. (see diagram below).

3.3. Verifying Failure Hypotheses

For the failure to occur spontaneously, all the components of the method that the team was attempting to verify had to be present within the system or its nearby environment.

Therefore, to verify a hypothesis:

1. The team had to determine if all the components necessary for this method to be realized were present as available resources
2. Next the team determined whether the method with all resources available provided the complete solution to the Inverted Problem.
3. Lastly, they developed a simple test to verify each hypothesis by eliminating one of the conditions required for it to be realized. If after this the failure did not occur, the hypothesis could be considered further as the root cause of the failure.



4. Preventing or Eliminating Failures

The ideal way to prevent a failure is to eliminate its causes. There are many reasons, however, why this might not be possible – it might be too expensive, too late, outside the teams area of responsibility, etc.

The Preventing or Eliminating Failures section of the Failure Prediction process included the following software supported actions:

4.1. Prevention Problem Formulation and Concept Development

Formulating the direct problems for preventing, eliminating or reducing the failure was done by using the graphic models of the hypotheses and attacking critical useful and harmful functions, one-by-one. This process was facilitation via the continued use of the AFD—Failure Analysis software.

The previous diagram included a harmful function "outer ring rotation (movement)". The Problem Formulation process was used to formulate this function. It revealed the following:

One of the Main Directions that was formulated was:

> Eliminating [the] (Outer ring movement) to prevent [the] (Bearing walk-out from central bore).

Main Direction: Eliminating the Failure
This Direction was then refined by the software to consider the various ways the drawback might be eliminated, from the most radical to the most reasonable:

- Remove or change the source of harm
- Modify the harmful effect
- Counteract the harmful effect
- Isolate the system from the harmful effect
- Increase the system's resistance to harmful effect
- Modify or substitute the effected object

Each of those Refined Directions was then used to identify ways to eliminate the failure. The following are examples of this phase of the work.

➢ Modifying the harmful effect

- Consider changing the undesired effect in order to make conditions secure for the system.

  From this "Idea 1" was developed:

  > Change the direction of movement - this way the bearing will not go out of central bore and will not damage other parts.

- Counteracting the harmful effect – Consider eliminating a harmful effect by using another effect.

  > For this purpose, consider:
  > - adding another harmful effect available in the system
  > - opposing an action that causes a harmful effect with another, similar action
  > - neutralizing the harmful effect with a countering effect

  From this "Idea 2" was developed:

  > Based on the mechanism of bearing movement being spiral grooves (like threads) that cause the mechanism to move out of the bore as a result of the deflection wave. Counteract this by reversing the spiral grooves (threads) to apply forces in the opposite direction.

➢ Modifying or substituting the object effected by harm

If it is impossible to protect the object from the harmful effect, consider changing the object's properties or even replacing the object.

From this "Idea 3" was developed:

Replace the needle bearing with a journal bearing

Another of the Main Directions that was formulated was:

> Stopping the harmful effects of [the] (Outer ring movement) that are caused by [the] (Axial force generation) and (Sun gear rotation around the shaft).

This Direction was also refined to consider the various ways the drawback might be eliminated, from the most radical to the most reasonable:

- Stopping the harmful effects of the failure
- Reducing the effect
- 'Blending in' defects
- Transient using of a harmful effect
- Facilitating detection
- "Sugar coating the pill"

As before each of those Refined Directions was then used to identify ways to eliminate the failure. The following are examples of this phase of the work.

➢ **Facilitating detection**

- If it is impossible to eliminate a harmful effect that leads to a search (for lost or damaged systems or for individuals responsible for the harm), consider making provisions in advance that will facilitate the search.

  From this "Idea 4" was developed:

  When bearing starts to move from its position and touches other parts, it creates damage. Use the sound of related to the small initial movement to signal that the problem is starting to occur.

Another of the Main Directions that was formulated was:

> Stopping the harmful effects of [the] (Bearing walk-out from central bore) that are caused by [the] (Outer ring movement) and (Outer ring rotation).
>
> From this "Idea 5" was developed:
>
> Changes in the transmission design could be made to eliminate the possibility for contact between the bearing and other parts.

The process continues and another Main Direction is formulated to provide the following:

> Preventing [the] (Bearing walk-out from central bore).
>
> From this "Idea 6" was developed:
>
> Install an mechanism on the shaft to stop the bearings movement.

Another Main Direction was formulated to provide the following:

> Eliminating [the] (Outer ring rotation) to prevent [the] (Bearing walk-out from central bore).

➢ **Increasing the system's resistance to the harmful effect**

In particular:

- decrease the sensitivity of the system to a harmful effect, or create immunity to the effect
- provide in advance for immediate restoration of the system by replacing or repairing portions that are destroyed or damaged

From this "Idea 7" was developed:

Glue the bearing in the appropriate position.

From this an additional "Idea 8" was developed:

Make the bearing interface elastic - this allows movement to generate a return force

Another of the Main Directions that was formulated was:

> Stopping the harmful effects of [the] (Outer ring rotation) that are caused by [the] (Tangential force generation) and (Sun gear rotation around the shaft).

From this “Idea 9” was developed:

Make grooves in central bore circular instead spiral.

Another Main Direction that was formulated was:

Eliminating [the] (Sun gear deformation) to prevent [the] (Helical deformation of sun gear) and (Rotating wave of deformation).

Increasing the system's resistance to the harmful effect.

From this “Idea 10” was developed

Make the sun gear more rigid.

- **Modifying or substituting the object effected by harm**
  If it is impossible to protect the object from the harmful effect, consider changing the object's properties or even substituting the object.

From this “Idea 11” was developed:

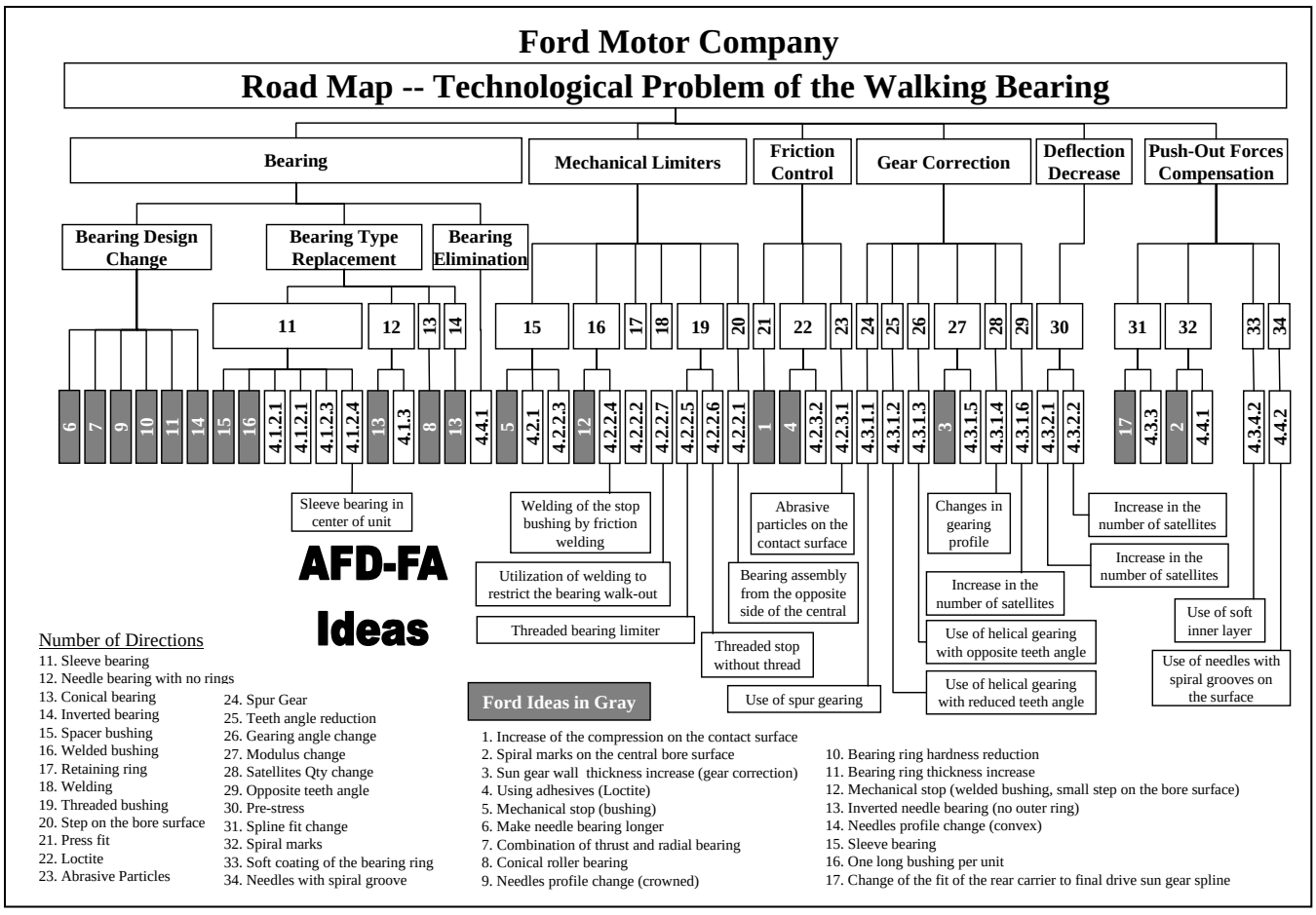
Instead of making the sun gear more rigid, make the satellites a little less rigid – this will reduce deformation of sun gear.

This process was continued with the development of a broad cross-section of ideas being combined and developed into approaches (concepts) for eliminating the failure.

5. Evaluation of the Results

The objective of the Evaluating Results stage of the process was to enhance the ideas that were developed for failure prevention/elimination. The team attacked this with the purpose of enhancing these ideas and planning for their successful implementation.

The selection of the Prevention Concepts was based on the analysis, identification of secondary problems and ranking of the concepts. The analysis and solutions that were selected are not disclosed in



this paper but were based on business needs such as the repair of the sun gear mechanism in the field to resolve warranty claims and actions were taken to eliminate the problem on future generations.

The Creation of a Benchmark

A comparative analysis of Ford's engineers initially targeted areas of search for a solution verses the work done as a result of AFD—Failure Analysis is denoted in the diagram on the previous page. The grayed boxes indicate 18 areas identified by Ford's engineers. The use of AFD—Failure Analysis revealed an additional 28 areas and the combination of a select group of these new ideas resulted in the invention of the failure mechanism. The final result was the identification of ways to eliminate the problem and prevent the failure in the future.

SUMMARY

Ford's SMEs coupled with the expertise of Ideation TRIZ Specialists working in parallel successfully applied the AFD—Failure Analysis process. The combination of expertise, experience, dedication, and engineering know-how of the Ford/Ideation team lead to the successful resolution of this failure mechanism.

Ford management and team commitment to solving the problem was a critical factor in the process, andthat lead to the successful completion of this project.

The AFD—Failure Analysis System sSoftware provideds a structured, systematic approach that utilized both analytical and knowledge--base tools. Through the utilization of a structured questionnaire,, software-based problem formulation that reveals an exhaustive set of Directions and a structured knowledge base for inventing and eliminating the failure provided the required value. These tools significantly expanded the ability of the team to go beyond traditional tools, such as FMEA, Design of Experiments and trail and error attempts to solve this previously unsolved, two-year old warranty problem.

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