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Application of TRIZ to Develop an In-Service Diagnostic System for a Synchronous Belt Transmission for Automotive Application

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Abstract

Development of robust diagnostic solutions to monitor the health of systems and components to ensure through life cost effectiveness is often technically difficult, requiring an effective integration of design development with research and innovation. This paper presents a structured application of TRIZ and USIT (Unified Structured Inventive Thinking) to generate concept solutions for an in-service diagnostic system for a synchronous belt drive system for an automotive application. The systematic exploration through TRIZ and USIT methods has led to the development of six concept solution ideas directed at the functional requirement to determine the state or condition of the belt. The paper demonstrates that the combined deployment of TRIZ and USIT frameworks is a valuable approach addressing difficult design problems.

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Keywords TRIZ; Unified Structured Inventive Thinking; condition monitoring; design solutions

1. Introduction

Development of effective solutions for maximizing the through-life cost effectiveness of complex systems has become a priority for all companies engaged in product design and development. Advancements in mechatronic systems design, as the fusion of electro-mechanical systems with sensors and advanced software for control and optimization of in-service performance, has enabled automotive OEMs to develop powertrain solutions that deliver enhanced performance and refinement while meeting increasingly stringent emissions legislation over the lifetime of the vehicle, within a very cost-conscious environment. Robust diagnostic systems are required to monitor the health of the systems both as a compliance requirement (e.g. emissions legislation) and to ensure through-life cost effectiveness.

The development and introduction of mechatronic machine elements [1], where sensors and software are used to enhance the functionality of the components to diagnose their own state of health, is an important research avenue with significant potential for the increase of through-life cost effectiveness of automotive systems. Development of such solutions is often technically difficult and requires an effective integration of research and innovation.

Systematic approaches to innovation, underpinned by tools like TRIZ, have been adopted by many organizations to enhance their ability to overcome complex design problems with effective, innovative solutions. The aim of this paper is to demonstrate the effectiveness of a systematic deployment of TRIZ to generate concept solutions for a technically difficult problem – development of an in-service diagnostic system for an engine timing belt.

1.1. Overview of the problem

Synchronous belt transmissions (or "timing belts") are widely used in automotive engine applications. They represent an attractive cost, weight, complexity and quality

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advantage over chain or gear camshaft drives [2, 3]. However, their use is limited by the disadvantage that a sudden (with no warning) timing belt failure in service can lead to catastrophic effects on the engine. This risk is typically managed through replacement at prescribed service intervals, causing cost and inconvenience to the customer. In comparison, chain and gear camshaft drives have a nominal life similar to that of the engine and do not present the risk of a sudden catastrophic failure.

Synchronous belt technology has advanced considerably in recent years, to the extent that timing belts are now capable of providing a service life comparable with the engine life (typically 250,000 km). While this has the potential of a significant customer satisfaction enhancer, given the high severity of a belt failure in service, this risk would have to be mitigated, e.g. through the introduction of a "warning" device based on an in-service diagnostic system. However, the development of a cost effective yet reliable diagnostic system for the polymeric composite materials that make up a timing belt is technically difficult, with added challenges given the harsh conditions in which the belts are operating.

1.2. Philosophy of the approach

The research presented in this paper is based on using structured inventive thinking tools and principles – TRIZ and USIT (Unified Structured Inventive Thinking) to identify potential concept solutions for the timing belt in service diagnostic system.

The paper will give a brief overview of the TRIZ and USIT methodology, followed by the detailed presentation of the application of TRIZ / USIT to the timing belt diagnostic problem. Several technically feasible solutions generated through this analysis will be discussed and evaluated from an engineering design point of view.

The paper will then reflect on the effectiveness of the TRIZ and USIT methodology to develop innovative solutions for in-service diagnostic systems for technically difficult problems.

2. Overview of TRIZ / USIT

Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ), translated from Russian as 'Theory of Inventive Problem Solving', is a structured framework for the conceptual design of engineering solutions where functional contradictions exist [4]. Developed by Genrich Altshuller and his colleagues in the former USSR in the late 1940s and 1950s, the TRIZ framework of knowledge-based tools was created out of an extensive study of worldwide patent applications whose conclusion was that a limited number of design solutions were truly pioneering inventions and that the rest were previously known ideas and concepts reused in a novel way [5].

2.1. The TRIZ framework

TRIZ considers the early stages of engineering design to be a process of inventive problem-solving. Within the TRIZ framework a number of problem solving analysis methods and tools have been developed, such as Substance-Field analysis [4, 5, 6], Required Function analysis [5] and the ARIZ or the Algorithm for Inventive Problem Solving [5, 7].

Contradiction analysis is a primary TRIZ tool that is based on Altshuller's discovery that the overwhelming majority of patented solutions to problems were created using just 40 inventive principles and that all functions could be described using 39 basic parameters [5]. Altschuller concluded that the main issue when attempting to create viable solutions to engineering problems was that functional requirements are often in conflict. Conflict is caused by either a technical contradiction, where improvement of one functional parameter is detrimental to another, e.g. increasing vehicle size to improve passenger comfort will increase weight and fuel consumption, or by a physical contradiction of states, e.g. a blacksmith requires that a metal piece is hot enough to work but is cool enough to hold. Contradiction analysis uses a matrix tool (the Contradiction Matrix) to identify a limited number of inventive principles that allow the fulfilment of contradictory functional requirements without compromise [5, 8].

Included within the TRIZ framework and underpinning the analysis methods and tools are a number of key concepts and principles that support the identification and treatment of technical contradictions. For this work, the most significant of these is the principle of *Ideality*, which stipulates that all engineering systems should evolve toward increasing degrees of ideality and encourages the problem solver to conceptualise an Ideal Final Result (IFR). The IFR delivers all the desired functionality without harmful or unwanted effects and none of the costs of the original problem. The ideal system is acting as pure function such that it occupies no space, has no weight, requires no additional energy or maintenance, delivers benefit without harm and is capable of producing the desired effect all by itself [9]. Every 'real' system is less than ideal in that it performs functions which generate both useful effects, i.e. the desirable functions of the system, and harmful effects, i.e. those outputs of the system that are considered to be undesirable, e.g. the generation of heat and noise as a by-product of the combustion process in an engine. The design objective is therefore to maximize useful functionality whilst keeping the harmful effects to a minimum. The Ideality principle is extended through Functional Analysis and Trimming that is aimed at improving value of the system where the functions of a system are identified and analysed with the intent of increasing the value of the product by eliminating parts, and thus reducing cost, but retaining the desired functionality [7]. Solutions can be assessed using an IFR coefficient calculated using the equation below [4]:

$$\text{IFR} = \frac{Sum\ of\ useful\ functions}{Cost + Sum\ of\ all\ harmful\ functions}$$

There are four stages in the process to apply the Contradiction analysis methodology:

1) The problem should be defined and the IFR should be conceptualised to establish a quality benchmark for solution ideas.
2) The system should be decomposed to analyse it's characteristics in terms of the technical characteristics presented by TRIZ. The key task is to identify conflicts or contradictions that exist in the current system and

decide whether to focus on improving useful characteristics and/or decreasing the harmful characteristics of the system.

3) The contradictions that exist within the system should be clearly stated, remembering that a contradiction occurs when the improvement of one characteristic will cause a negative change in performance of an opposed characteristic.
4) The contradictions stated in step 3 are then resolved using the Contradiction Matrix [8].

2.2. Unified Structured Inventive Thinking (USIT)

Unified Structured Inventive Thinking (USIT) is an extension of TRIZ developed by Ed Sickafus at the Ford Motor Company in the 1990s, aimed at simplifying the development of solutions for common engineering problems [10]. Within the USIT framework, two methods have been developed: the 'Closed World' method, typically used for improvements to existing systems; and the 'Particles' method aimed at new system design. The latter method was considered in this work.

The Particles method within the USIT framework was developed out of the TRIZ concept of 'smart little people' where the designer is encouraged to use his imagination to visualise small particles to carry out tasks to solve the problem at hand in four stages:

1) The problem is defined by collecting relevant information to give an accurate but concise statement of the problem. Non relevant information is discarded so as not to waste time.
2) Objects within the system or in the surrounding environment are identified for quickly establishing the creative environment.
3) The ideal final result is then conceptualised using problem-to-solution sketches to establish the quality benchmark for solution ideas.
4) An And/Or tree is then drawn to form a hierarchical arrangement of particles' actions from the ideal solution state back to the original problem situation [10].

To generate multiple conceptual solution ideas, the USIT framework sets out a set of five 'solution procedures';

1) Uniqueness – to consider features of the problem that give it unique (e.g. spatial or temporal) characteristics of its own;
2) Dimensionality – refers to an object's attributes. Changing dimensionality may occur when an unused attribute of the system is brought into use or an attribute in use is no longer needed;
3) Distribution – to distribute functions over time or space;
4) Pluralisation – to make copies of objects or parts of objects may be used in different ways to create a solution;
5) Transduction – to create chains of attribute-function-attribute links can be formed to lead from one object to another [10].

3. Timing belt problem analysis using TRIZ/USIT

A timing belt typically comprises of helically wound tensile load carrying cords inside an elastomer compound which forms the backing and bulk of the belt teeth, and a polymide facing fabric to cover the belt teeth and protect them against wear [11]. The literature commonly refers to four failure mechanisms associated with timing belt failure; tooth root cracking (TRC), cord delamination, fabric separation and belt back cracking [11, 12], of which TRC (illustrated in Figure 1) is commonly seen as the dominant failure mechanism [13]. Studies have shown a reasonable correlation between TRC fatigue life and tooth load and deflection [14], and a good agreement with dynamometer studies of time to failure [13]. Such studies have been instrumental in proving belt design solutions against system durability requirement of 10 years / 250k km, with no need for costly service replacement. However, given the high impact of failure, the development of an in-service belt failure warning system is a desirable countermeasure.

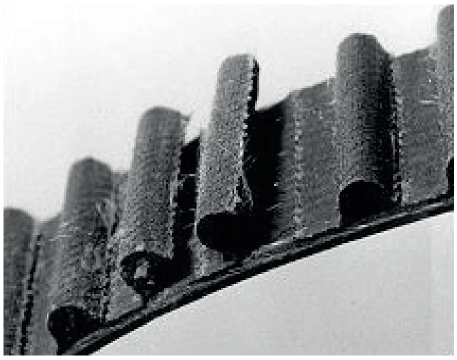

Fig. 1 – Timing belt failure mechanism; tooth root cracking

The technical difficulty associated with such a development stems from the fact (similar to other high cycle fatigue problems) that the time between fault initiation (i.e. TRC initiation) and catastrophic failure is very short. Studies [11] have also discussed that, specifically in relation to TRC, there is no reliable correlation between any belt parameter (such as belt hardness or presence of cracks at visual inspection) and the remaining life of the belt.

3.1. Design objective definition and the Ideal Final Result

Having articulated the problem, the design objective can be stated as:

"*To improve the ability to measure timing belt condition and detect failure in the mileage/time interval between initiation and catastrophic failure*."

The Ideality principle suggests that the Ideal Final Result (IFR) should require no intervention, adds no weight to the timing belt system and takes up no space. In this case study it can be stated as:

"*A new timing belt system that is itself capable of detecting and measuring accumulated damage and reporting imminent belt failure before the event*."

3.2. Contradiction identification and analysis

The design objective definition and Ideality principle analysis indicates two technical contradiction problems to be resolved; the design objective requires an improvement in failure detection capability (the useful effect), but function is constrained within a very small time/mileage interval; the Ideality principle requires that the chosen system must deliver the improvement in failure detection capability whilst minimising any increase in system complexity (a harmful effect). For a contradiction analysis, these must be expressed in standard form; the 'improving' feature is the ability to detect and measure (feature 37); the 'worsening' features are the time available to measure belt condition (termed 'Loss of time' – feature 25) and an increase in system complexity (termed 'Device complexity' – feature 36).

Figures 2 and 3 show extracts from the Altshuller Contradiction Matrix [15] for the two contradictions indicating the Design Principles that should be considered to derive solution concepts. These are summarised in Table 1.

Improving Feature	Worsening Feature	24 Loss of Information	25 Loss of Time	26 Quantity of substanc	27 Rel	28
36	Device complexity		6, 29	13, 3, 27, 10	13, 35, 1	2, 26, 10, 34
37	Difficulty of detecting and measuring	35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18	27, 40, 28, 8	26, 24, 32, 28
38	Extent of automation	35, 33	24, 28, 35, 30	35, 13	11, 27, 32	28, 26, 10, 34

Fig. 2 – Contradiction Matrix: Difficulty of detecting vs Loss of time

Improving Feature	Worsening Feature	35 Adaptability or versatility	36 Device complexity	37 Difficulty of detecting and measuring	38 Extent of	39
36	Device complexity	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 24	12, 17, 28
37	Difficulty of detecting and measuring	1, 15	15, 10, 37, 28	+	34, 21	35, 18
38	Extent of automation	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26
39	Productivity	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+

Fig. 3 – Contradiction Matrix; Difficulty of detecting vs Complexity

Table 1 – Summary of Contradiction Matrix suggested Design Principles

Design Principle	Suggested solution
18 – Mechanical vibration	Use natural frequency properties to identify changes of state
28 – Mechanics substitution	Replace the visual inspection with other sensory means.
32 – Colour changes	Use a colour change to indicate changing properties or states that can be seen by a calibrated colour detector.
9 – Preliminary anti-action	Develop technology to increase life so that inspection no longer becomes necessary.
15 – Dynamics	Divide an object into parts, make it flexible and increase the degree of free motion.
10 – Preliminary action	Perform before it is needed, the required change of an object.
37 – Thermal expansion	Use multiple materials with different coefficients of thermal expansion

3.3. USIT Particles solution development

In order to use the USIT methodology to expand the derivation of design solution concepts out of the Contradiction Analysis, the design problem was redefined in terms of the objects present. The objects in this problem are: (1) the timing belt and (2) information. In the initial problem situation there is a timing belt in an unknown condition. Therefore the problem can be redefined as;

"*How to determine the instantaneous state (condition) of the timing belt.*"

In the ideal solution the assumption is that the timing belt is at an equivalent point in time but information as to its condition is known. Therefore the solution statement is;

"*The instantaneous state (condition) of the timing belt is known*"

The next stage in the process is to identify the function of particles in the ideal solution. For this case study, the function of the particles is to interrogate the timing belt and transfer condition information to a detection device. To understand how particles could carry out this interrogation, the properties of the timing belt that are relevant to its condition and could be detected by particles have been determined. These are given in Table 2.

Table 2 – Detectable properties of timing belt damage

Property	Description
Colour	Colour change might be used to indicate stress concentrations.
Smell	Smell might indicate the presence of specific chemicals released due to the damaged condition of the belt.
Acoustic (natural frequency)	Changes in the belt natural frequency could indicate changes in condition. (Note: To measure this effect, particles would need to generate sound and then detect sound).
Mechanical texture	Changes in stiffness or elasticity might indicate changes in local material properties.
Dimensional	Dimensional changes might indicate belt strain under load during operation.
Performance	Changes in phase and frequency between the crankshaft and camshaft pulley speed signals might indicate changing mechanical properties of the belt under load during operation.

Figure 4 illustrates the And/Or tree for the timing belt condition monitoring problem, showing the relationships between the ideal solution and particle actions. If the interrogation is done using sensors, then electrical output from the sensors would be expected. Transferring electrical information to a control circuit is a straightforward engineering exercise, thus the focus of this work is on interrogation issues.

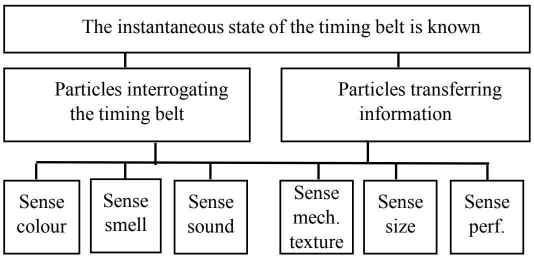

Fig. 4 – And/Or tree for the timing belt problem

The final stage is to convert timing belt properties to objects that embody the identified functions and attributes using the USIT solution procedures as guidance. Table 3 is a summary of solution concepts derived in this work using the TRIZ Contradiction Analysis method and the Particle method.

Table 3 – Summary of concept solutions

TRIZ Design principle	Timing belt condition properties	USIT solution procedure employed	Suggested solution concepts
18 – Mechanical vibration	Acoustic	Pluralisation	Ultrasound crack detection system.
28 – Mechanics substitution & 10 – Preliminary action	Smell	Transduction	Embedded Inert gas that is released during cracking + detection system.
32 – Colour changes & 10 – Preliminary action	Colour	Dimensionality	Belt material changes colour due to localised stress concentrations + detection system.
15 – Dynamics	Performance	Pluralisation	Multiple accelerometers added to crankshaft and camshaft pulleys to measure differences in angular velocity and phase in each speed signal as an indicator of belt condition.
15 - Dynamics	Dimensional	Pluralisation	Introduce multiple belts to mitigate catastrophic failure
37 – Thermal expansion & 9 – Preliminary anti-action	Mechanical Texture	Distribution	Use belt material thermal expansion properties to preload the timing belt in opposition to dynamic loading to reduce operating stresses.

4. Discussion

The aim of this paper was to apply a structured design process to the generation of solution concept ideas for an in-service diagnostic system for a synchronous belt transmission for automotive application. The review of prior literature on the sudden and catastrophic nature of timing belt failure, the likely costs to the customer of such a failure and the challenges of failure prediction highlighted the need for such a solution. At this early stage of the design process, the intent was to generate concept ideas without particular concern for practicality as creative solutions, however impractical, may spawn useful and innovative hybrid solutions at a later stage.

The aim of the paper has been achieved through the generation of six concept solutions each directed at the functional requirement of determining the instantaneous state or condition of the timing belt during operation. There is one solution for each of the timing belt properties identified during the design process that could be measured to indicate belt condition and which, if calibrated correctly, could warn that the belt is approaching the end of its useful life before catastrophic failure occurs.

The concept solution design process draws on the TRIZ and USIT frameworks that have been embraced by engineering industries over the last two decades [10, 15]. The utilisation of the TRIZ/USIT frameworks has been described as a *process* because it has used tools in a defined and structured sequence and there is a clear information flow between the tools and the defined steps. The benefit of using this structured process is that each concept idea is generated out of, and can be traced back to, the utility functional requirement to be able to determine the instantaneous state or condition of the timing belt during operation.

The tools and principles used in the process are well known and each has been valuable in helping to address the design problem. The drive to define the initial problem and the articulation of the ideal final result has been fundamental in framing the problem and setting out the vision and direction for subsequent analyses. Clear problem definition has enabled the identification of the technical contradictions present in the design problem. Similarly, contradiction analysis has proved to be intuitive to use, yet powerful in identifying the relevant design principles for solution idea generation. The particles method has enabled the expansion of these ideas, and using a series of solution procedures has been highly effective in the identification of potential solution concept ideas for further investigation.

A limitation of the combined TRIZ / USIT process is that the generation of the detectable timing belt properties and their solution concepts was carried out by “brainstorming”. Whilst the TRIZ/USIT tools are effective in prompting highly creative ideas, the lack of structure afforded by brainstorming means that full property identification cannot be guaranteed and therefore concept solutions can remain unidentified. Other authors [16, 17] have proposed a more systematic approach to concept solution generation using discursive methods (e.g. systematic studies of physical processes, use of classification schemes and design catalogues) and methods for combining solutions (e.g. systematic combination). A more structured process for solution concept generation might include systematic methods in combination with the creative TRIZ/USIT tools to maximise design potential.

5. Conclusions

This paper presented the findings of a design study to generate concept solution ideas for an in-service diagnostic system for a synchronous belt transmission for automotive application.

Six concept solution ideas have been generated that can be traced back to the functional requirement to be able to determine the instantaneous state or condition of the timing belt during operation.

One concept solution has been identified for each of the timing belt properties identified during the design process that could be measured to indicate belt condition and which, if calibrated correctly, could warn that the belt is approaching the end of its useful life before catastrophic failure occurs.

During this early stage of the design process concept solutions have been generated without concern for practicality so as not to cut off innovative hybrid solution creations at a later stage.

The work has shown that a structured design process based on the combined TRIZ/USIT frameworks can be used to create solution concept ideas and that the tools are valuable in helping to address the design problem. The particular benefits are in the use of the tools to frame the problem and set out the vision and direction for subsequent analyses, to identify technical contradictions present in the design problem and be highly effective in the identification of potential solution concept ideas for further investigation.

The need to brainstorm ideas for object properties and subsequent solution ideas indicates a limitation of the combined TRIZ/USIT process as it does not guarantee that all properties are identified, and therefore potential concept solutions can remain unidentified.

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