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TRIZ-Based Root Cause Failure Analysis For Hydraulic Systems

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Abstract

Analysis of root cause failure mechanisms in hydraulic systems suggests that poor overall system specification, leakage and contamination issues are the dominant failure contributors. The paper examines how the Russian Theory of Inventive Problem Solving, TRIZ, is beginning to be applied in the specification and design of hydraulic systems and components. Several of the key TRIZ tools, methods and strategies – Contradiction elimination, Ideal Final Result, Trends of Evolution, and Function Analysis have been deployed on a number of case study examples. These examples include leak-free coupling and self-cleaning filter component design studies, and an examination of whole system energy management issues.

Keywords

TRIZ, system specification, leakage, contamination

Introduction

Hydraulic systems are robust. Robust but not invincible. The hydraulics industry has, generally speaking, been quick to capitalise on the former, and slow to recognise the latter. Rising customer expectations on parameters like time between overhaul and time between failure have reached a point where they often exceed the inherent capability of today's hydraulic systems. Existing design paradigms for individual components are no longer appropriate. Existing design paradigms for integrated hydraulic systems are no longer appropriate. The answer does not lie in the traditional route of adapting existing ~~designs with after-the-event re~~medies; these make the product more expensive

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and, more often than not, shift the problem rather than remove it. After-the-event design is the ultimate compromise.

Design for reliability – ‘design for robustness’, ‘through-life design’ – means thinking about failure issues on day one. Causes of failure in hydraulic systems are, qualitatively at least, relatively well known. The two single biggest failure issues are leakage and contamination. The single biggest root failure cause is poor specification.

TRIZ is an extremely powerful Russian problem definition and problem solving method. TRIZ is built on the knowledge of mankind accrued across the global patent database. It is also a methodology built on a ‘design without compromise’ premise. It guides engineers towards getting the specification right. It guides engineers out of existing design paradigms into constructive and valuable new ones.

The objective of the paper is to demonstrate how TRIZ can and has been used to design inherently better – more reliable – hydraulic components and systems. A number of case study examples are presented. Each study focuses on one or more of the key failure related issues:-

- Using TRIZ to get the specification right – a look at system heat management from the perspective of both overall fluid power system technology evolution trends versus heat exchanger design strategy, using an example from a mobile application
- Using the Function Analysis and Ideal Final Result parts of TRIZ to conduct upfront root cause failure analysis of systems, and then using ‘Trimming’ techniques to derive the ‘right’ minimum life-cycle cost design solution – an application looking at the design of a simple, cheap, self-cleaning filtration system.
- Case studies examining the use of TRIZ root-cause contradiction elimination methods to help in the realisation of leak-free coupling and connector designs.

Most real world organisations are caught in a constant battle to produce ever more and ever better products with ever fewer resources.

Fewer engineers with more to do is a combination which usually leads to a strong focus on fire-fighting today’s problems with today’s tools and techniques. The ‘quick-fix’ is very much the order of the day.

All too often, the ‘quick fix’ turns out to be no fix at all. At least not in terms of overall business performance. The reason for this is very simply that by fixing the symptoms of a problem – rather than the root causes – we tend to generate a new solution which is fundamentally more expensive to produce than the old one. Adding a palliative is very much easier than finding a root cause. Especially when time is short.

Russian naval officer and engineer Genrich Altshuller had the idea that all of the examples of ‘good’ design practice – the designs which succeeded in achieving maximum functional benefit from minimum use of resource – followed common solution strategies. He also felt that these strategies could be systemised. And so Teorija Rezhenija Inzhenernyh Zadach (TRIZ) – or, in English, ‘Theory of Inventive Problem Solving’, was born.

TRIZ research began in 1946 with Genrich Altshuller’s hypothesis that there are universal principles of invention that are the basis for creative, technology advancing, innovations *[1]*. Altshuller believed that if these principles could be identified and codified, they could be taught to people; and thus could make the process of invention more predictable. TRIZ research has proceeded in several stages over the last 50 years, now accumulating over 1500 person-years of scientific study and going far beyond Altshuller's initial hypothesis. The three primary findings of the research are:

1. **Problems and solutions were repeated across industries and sciences**
2. **Patterns of technical evolution were repeated across industries and sciences**
3. **Significant innovations used scientific effects outside the field where they were developed.**

Much of the practice of TRIZ consists of learning these repeating patterns of problems-solutions and patterns of technical evolution, and methods of using scientific effects, and applying the general TRIZ patterns to the specific situation that confronts the developer. Figure 1 describes this process graphically.

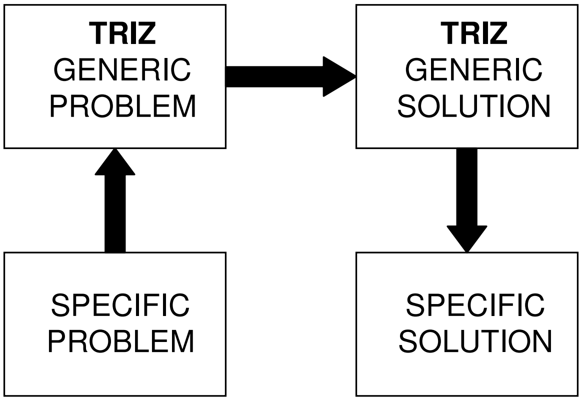


Figure 1 – *The General Model For TRIZ Problem Solving*

Altshuller's work on problem classification and the discovery that there are only a very small number of Inventive Principles available to the engineer is already profoundly changing the systematic innovation picture. That there are only these small number of principles has, for example, meant their systemisation in software form has been relatively easy. The emergence of a number of commercial packages built around TRIZ ideas *[2]* is therefore not surprising.

This concept of identifying the contradictions in a design and correlating them to how other inventors have solved the same types of problem is but one element of what is now a much broader TRIZ methodology covering:-

- Trends of technology evolution classified in terms of generic function-based parameters.
- Classification of physical, chemical, and mathematical effects into a function-based database structure.
- The concept of 'Ideal Final Result'; a means of first helping to define the problem to be solved and then a method for establishing the route towards the optimum (compromise-free) solution to that problem.
- A Function Analysis system modelling methodology and a corresponding database of what Altshuller described as 'Standard Inventive Solutions'.

- A method – known as the Algorithm for Inventive Problem Solving (ARIZ) – through which inventors are able to classify and discover effective means of solving complex problems.

The paper examines the Effects, Contradictions, Trends, Ideal Final Result and Function Analysis parts of TRIZ from a fluid power industry perspective, and looks at how TRIZ is being applied at the University of Bath to shift a number of design paradigms surrounding seemingly intractable problems.

Case Study 1: Flanged Joint/Leak-Free Coupling

In order to demonstrate some of the differences between the traditional design approach and the TRIZ approach, it is useful to look at the example of a flange joint design.

A flange joint is designed to carry a variety of loads and moments whilst simultaneously forming a satisfactory seal. Traditional logic says that if a flange is designed and tested and is found to leak, the way to rectify that leak is to do one of three things: 1) increase the bolt torque, 2) increase the number of bolts, or 3) add a gasket of some sort. Ninety-nine times out of a hundred, the ‘quick-fix’ solution to the leaking flange problem would be to do one of these things. In each case, however, although the immediate problem may have been fixed, the designer has merely solved the problem at the expense of something else in the design. Increasing bolt torque has degraded life expectancy of the joint, increasing the number of bolts has increased the overall weight and maintenance time, and adding a gasket has increased assembly and maintenance cost, and decreased life. The designer has in effect done no more nor less than find a different point on the same trade-off characteristic (Figure 2).

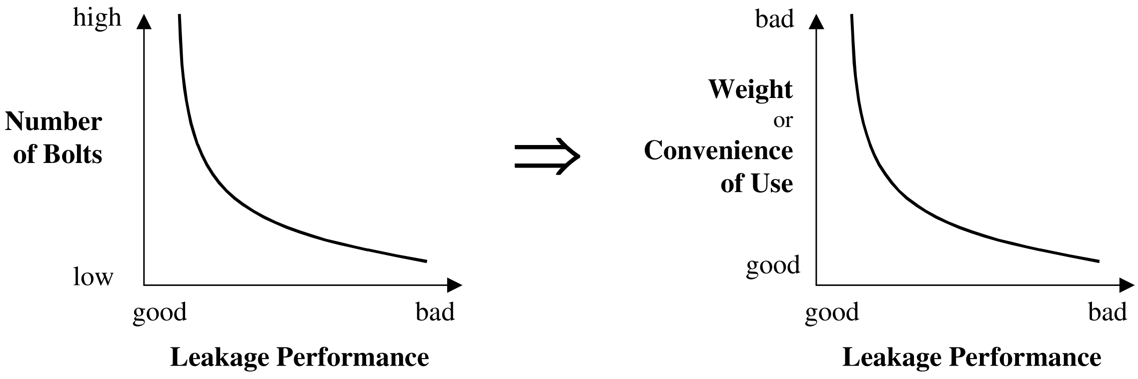


Figure 2 – *Typical Conflicting Parameter Design Trade-Off Scenario*

In TRIZ terms, the designer has designed by compromise. Given the same leaking flange scenario, TRIZ gets the designer to examine the design from a compromise-free perspective. In this case, ‘design without compromise’ will have been achieved if a design with good leakage performance AND a small number of bolts (low weight, high convenience of use) can be devised. Identification of this type of apparently paradoxical contradiction statement is an important aspect of TRIZ.

The Contradiction Matrix *[3] (Table 1 at end of paper)* provides a potent means of connecting such statements to inventive principles *(Table 2 at end of paper)* in which other engineers have managed to solve similar generic types of contradiction.

Reference *[4]* details the process by which the flange joint problem may be solved without compromise. Needless to say, it is possible to design a better seal with fewer bolts. The answer is illustrated in Figure 3. Tests on this type of flange joint *[5]* have demonstrated that it is actually possible to halve the number of bolts relative to conventional design practice.

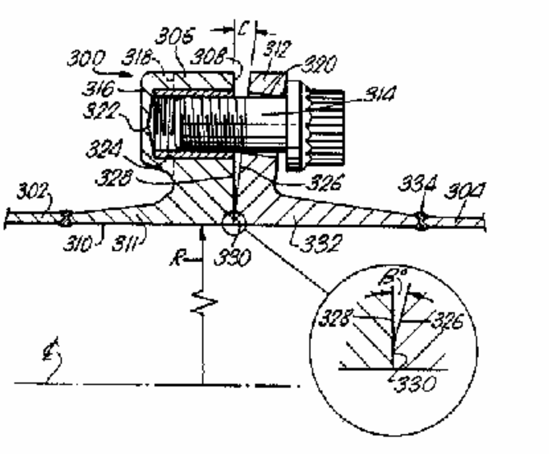


Figure 3 - *Fluid-Tight Joint With Inclined Flange Face, US Patent 5,230,540*

Leak-Free Coupling - No designer sets out to design a coupling that will leak. And yet over 300 million litres of hydraulic fluid go missing in Europe every year. Theoretically at least, the design picture is a well understood one; there are known design loads, L, and known material characteristics, S, and each has some kind of statistical spread – due to the various uncertainties present in systems – variations in material properties, variations in operating condition, degradation over time, etc. Design of a leak-free coupling, may be achieved by ‘simply’ ensuring there is no overlap between the load and strength characteristics – Figure 4.

The reality, of course, is that the two characteristics do overlap. The overlap occurs because – traditionally – the designer is also expected to keep a keen eye on other design requirements like cost, weight and manufacturability. Compromise occurs as the designer attempts to find the best balance between each parameter. Quite often cost – and particularly ‘initial purchase cost’ – becomes the dominant selection criterion; and leakage performance becomes compromised.

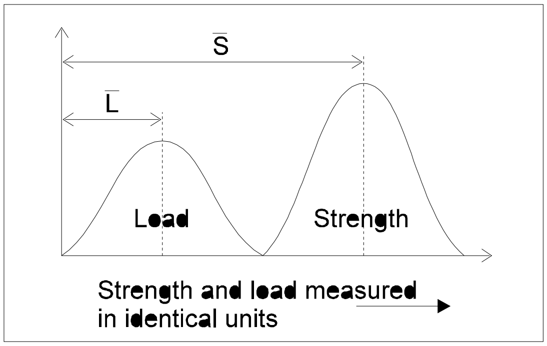


Figure 4 – *Load versus Strength –Ideal Design State*

The TRIZ root-cause compromise-elimination approach allows designers to escape from the traditional design strategy i.e., balancing different parameters (Figure 5).

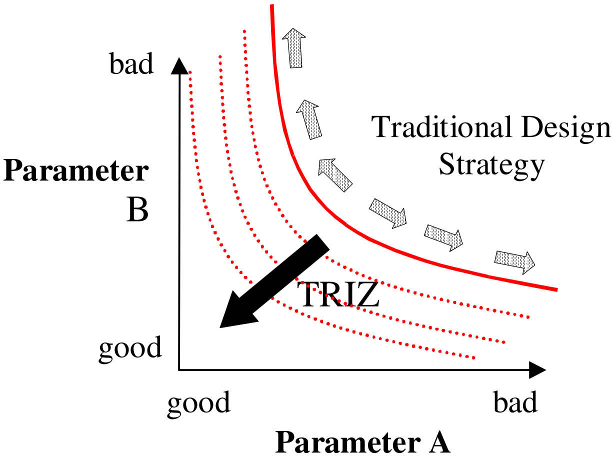


Figure 5 – *Traditional v TRIZ-based Approach to Root-Cause Design Contradictions*

The inclined flange face idea of Figure 3 is one such idea where the traditional coupling design paradigm may be modified in order to achieve good leakage performance **and** a low weight, low cost solution. The same contradiction-elimination perspective may also yield other significant root-cause problem solutions in other aspects of fluid power system design for true leak-free performance.

Case Study 2: Filters

A common starting point in TRIZ thinking is to look at the compromises and trade-offs present in the state of the art. In the case of filtration systems, those trade-offs include:-

* PHYSICAL SIZE
  - contaminant holding capacity,
  - pressure loss versus weight

* MEDIA TYPE
  - cleanable versus disposable

* BYPASS/NO-BYPASS

* MESH SIZE
  - circuit protection versus filter life

* OPERATING PRESSURE
  - size versus stability

Recognition of the trade-offs is a very good initial step towards removing them. Altshuller's trends of technology evolution provide one of the ways of determining how such trade-offs might be removed.

Strictly speaking not one of Altshuller's discoveries, but nevertheless consistent with all the trends he did discover is the universal trend towards increasing product 'ideality'. This idea was first discussed by Larry Miles *[6]*. Miles defined 'ideality' or 'value' as:

$$Value \; = \; Benefits \; / \; (Costs + Penalties)$$

The 'law' of increasing product 'ideality' in the context of fluid power filtration says that future systems will evolve towards greater benefit (better circuit protection), lower cost (cost of filter, life-cycle cost of system into which filter is designed) and reduced operating penalties (lighter filters, reduced volume, better disposability, etc). None of these should appear particularly surprising.

Miles' ideas are commonly expressed in terms of the S-curves of product evolution. S-curves show trends of increasing ideality through successive generations of product evolution.

Altshuller's trends of evolution discoveries are based primarily on analysis of the global patent database and have thus concentrated on the physical manifestations distinguishing one product generation from another. Among a host of patterns of evolution spotted by Altshuller *[1]* is the example of 'trimming'.

The 'Trimming' evolution trend (Figure 6) says simply that products will evolve to contain progressively fewer components. Generally speaking, the reduction will eventually be achieved with no decrease in product functionality.

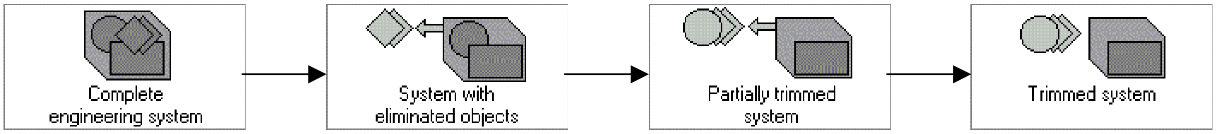


Figure 6 - *'Trimming' Evolution Trend*

Thinking now in terms of some of the current filtration system trade-offs and these possible evolutionary trends, it becomes possible to see how the latest generation of 'core-less' filters have evolved.

Conventional disposable filters involve disposal of the filtration medium and the supporting structure (element support, bowl, etc). Disposal occurs because the filtration medium is filled with contaminant. The support structure around the medium, however, has much useful life left. The ‘increasing value’ and ‘Trimming’ trends suggest that the support structure should be made re-usable and only the filtration medium is disposed of. Which is the exact principle in, for example, US patent 5,762,788 (Figure 7).

The ‘core-less’ filter is indeed a useful - perhaps 'generational' – advance in filtration technology. It ought to be possible to employ the evolution trend patterns to project further advances beyond this core-less unit.

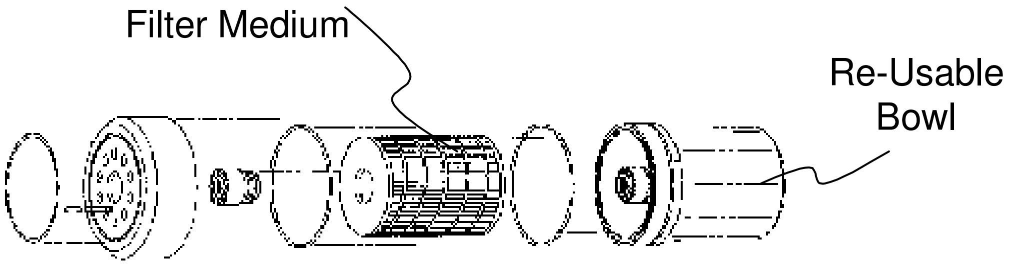


Figure 7 - *US Patent 5,762,788 ‘Fluid Filter Having Re-Usable Filter Housing and a Replaceable Coreless Filter Element’*

Altshuller, conceived the Ideal Final Result (IFR) philosophy as another means of assisting in the derivation of future technology advances. In effect, the IFR approach is a way of encouraging designers to look at the furthest evolution along the trend paths.

There are a number of ways in which the IFR of a product can be developed. One such means is to pass through the following sequence of questions:-

1) *What is the final aim?*
2) *What is the IDEAL FINAL RESULT?*
3) *What is the obstacle to this?*
4) *Why does this interfere?*
5) *Under what conditions would the interference disappear?*
   (What resources are available to create these conditions?)

In theory, passing through the questions successfully should lead to the required IFR solution – at least conceptually. In the case of the filter, for example, the following answers may emerge:

1) *What is the final aim?*
To remove contaminant from circuit (‘make the circuit invulnerable’ to contaminant could also be considered an effective strategy);

2) *What is the IDEAL FINAL RESULT?*
Contaminant removes itself from the circuit (Figure 8);

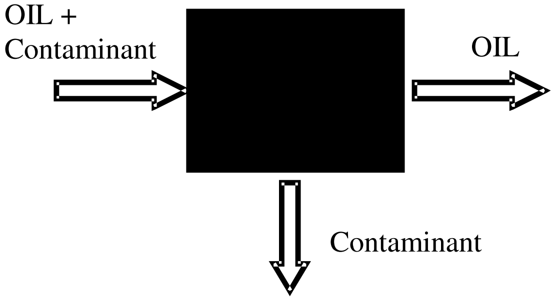


Figure 8 - *Filtration System 'Ideal Final Result'*

3) *What is the obstacle to this?*
Contaminant follows the oil flow.

4) *Why does this interfere?*
Since contaminant follows the flow, there is no means of removing it from the flow stream (except by using a barrier that stops contaminant but does not stop flow).

5) *Under what conditions would the interference disappear? (What resources are available to create these conditions?)*
contaminant able to move relative to flow
(contaminant has momentum, mass, shape, magnetic properties, etc).

Asked how many ways there might be to make a particulate contaminant 'move', evidence suggests engineers working in the particulate area might be able to name three or four.

Thinking more globally, other evidence suggests that the majority of engineers have working knowledge of perhaps 20-30 physical, chemical or mathematical effects, and maybe a passing knowledge of as many again.

The Invention Machine® software contains a massive database of such effects. One of the advantages of this database is in following the lead provided by Altshuller to classify the database in terms of **function**. So, for example, the database collects all the known ways of making particles move under a single heading. At present the number of ways of moving particles contained in the database is 33 (Table 3).

Some of these Effects will turn out to be more appropriate to the problem at hand than others. It is the job of the engineer to determine which is which. This will probably involve a significant amount of work. Likewise, the process of transforming a promising effect into a viable engineering design is equally tortuous.

In some instances, the technology associated with the effect will be insufficient to carry out the required function. For example, gravity alone will be insufficient to separate, say, a 3µm particle from oil in an acceptable (for a filtration system) period. In these cases, engineers are forced into a programme of research to improve the effect, or, more likely, there will be a need to back away from the IFR towards a solution which is viable. (See Reference *[7]* for an example of how such a process works in practice).

Table 3 – *Means of 'Moving Particles'*

* Gravity
* Inertia
* Acoustic Vibration
* Birds Beak Effect
* Corona Discharge
* Coulomb's Law
* Friction
* Diffusion From Limited Source
* Boundary Layer Entrapment
* Atomic Beam-Stimulated Desorption
* Diffusion Depth
* Dopant Segregation
* Laminar Flow
* Funnel Effect
* Hyperboloid
* Ion Conductivity
* Mobius Strip
* Magnetic Explosion
* Photophoresis
* Resonance
* Ferro-magnetism
* Diamagnetism
* Reuleaux Triangle
* Laminar Flow
* Resonance
* Vibration
* Turbulent Flow
* Electrets
* Photophoresis
* Thermophoresis
* Triboelectricity
* Pascal Law
* Ranque Effect
* Fluidisation
* Funnel Effect
* Electrophoresis

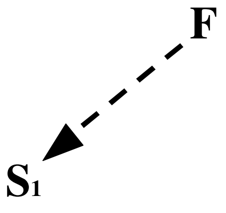
Meanwhile, in the case of the 'contaminant removes itself' Ideal Final Result, it appears that a solution may well be possible.

The problem is amenable to analysis by yet another of Altshuller's TRIZ tools – the S-Field Analysis part of TRIZ *[1]*. S-Fields are Altshuller's attempt to describe inventive problems in a manner analogous to chemical formulae.

'Fields' are external forces that may be applied to Substances (the 'S' in S-Field). There are six basic families of field:

- Gravitational
- Electromagnetic (electrical/magnetic)
- Nuclear – weak interaction
- Nuclear – strong interaction
- Mechanical
- Thermal.

Taking S_1 to represent a typical particulate contaminant, we are able to draw an S-Field for the current situation:



According to the IFR, we require to impart some kind of force onto the particle in order to separate it from the force. The dashed arrow indicates that this is currently an 'insufficient action'. Analysis of the available Fields along with use of the Effects database does not appear as though a (practical) field with sufficient force can be obtained. Probably the closest would be to use an electrical field (cf. electrostatic precipitator separation devices), although the low velocity requirements of such systems mean they would be too bulky (and expensive) for a fluid power application.

This ‘insufficient action’ S-Field scenario is one of a number of problem types classified by Altshuller. For each type of problem, he identified a number of Standard Inventive Solutions. For this particular case, one of the suggested solutions is, ‘if it is not possible to impart sufficient Field to the Substance directly, then impart it through a second substance'. The S-Field map for this suggestion is illustrated in Figure 9.

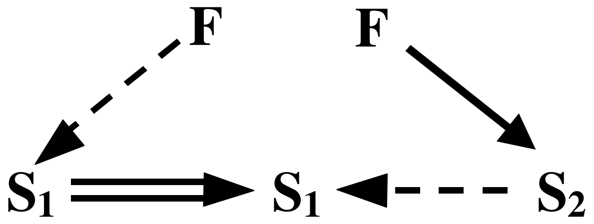


Figure 9 - *S-Field for ‘Ideal Final Result’ Fluid Power System Filtration Device*

Preferably, the second ‘substance’ S_2 will be an existing part (or a modification of an existing part) of the system surrounding the separator. Ideally, the Field applied to S_2 will be the simplest of the six possibilities.

Analysis of the ‘self-cleaning filter’ based on this S-Field has in fact revealed that a solution does exist. In keeping with the concept of using existing parts of the system (i.e. the overall fluid power system), preliminary calculations suggest that a self-cleaning filter offering:

- lower installed volume
- lower pressure loss
- higher pressure loading capability
- low part count (lower than for current barrier filters)
- low cost

can be achieved. In common with other studies *[8]* this case demonstrates a tendency to achieve many more side-benefits above and beyond the initial goal (which was ‘self-cleaning’ in this case) if ‘design without compromise’ can be achieved. A self-cleaning filter based on the S-Field work presented here is currently the focus of a patent application.

Case Study 3: Evolution of Pump Controls to Improve System Efficiency

In order to develop competitive advantage in what is a highly competitive market, companies manufacturing mobile equipment e.g., excavators and tractors, are increasing the sophistication of the hydraulic control systems available to the operator. In doing so they are adding to the demands on the fluid power system to dissipate energy e.g., within the reservoir, as increased temperatures effect viscosity and therefore performance levels.

As space restrictions limit the size of the oil reservoir on mobile equipment many manufacturers have to add additional components such as coolers and fans to control the heating problem. This increases the complexity of the auxiliary systems and adds significant cost.

To improve energy efficiency, and counter heating problems, fluid power system designers have evolved increasingly more sophisticated control strategies. Five control strategies are described below with the first three being used with fixed displacement pumps and the final two with variable displacement pumps.

1. Constant flow with maximum pressure limitation - This system always absorbs considerable power especially when flow is zero. Under this condition all the pump flow is relieved through the relief valve at maximum system pressure. The pump is therefore being operated at maximum power and as no useful work is being done by the system, all the power is dissipated as heat at the relief valve.

2. Constant flow with maximum pressure limitation and automatic unloading - The efficiency of the basic circuit can be improved by replacing the pressure relief valve with an unloading valve which automatically unloads the pump whenever the flow in the system becomes zero. Unlike the pressure relief valve, the unloading valve opens fully whenever the system pressure reaches its maximum value, permitting pump flow to be passed directly back to tank.

3. Variable flow with maximum input power limitation - Some systems require large flows at low pressure and only small flows at high pressure. Considerable saving in installation cost and overall efficiency can be achieved by using two or more fixed displacement pumps driven from a single prime mover of limited power. Such a system is more efficient as by selection of suitable pump flows and pressures the power required to drive the pumps for both low and high pressure conditions is the same.

4. Constant pressure systems - Introduction of variable displacement pumps permitted hydro-mechanical control (compensation) to provide a constant pressure irrespective of the flow demand. An equilibrium is reached when the delivery flow is such that the delivery pressure is close to (but slightly more than) the pre-set level. Such an arrangement is, in many applications, more energy efficient than a fixed displacement pump discharging flow, through a relief valve.

5. Load-sensing systems - There is a definite trend towards greater use of load sensing control, particularly in mobile applications. The aim is to vary both flow and pressure to suit the demand of the load, thereby saving energy. Unlike control pressures for pressure compensated pumps that are sensed inside the pump and reflect all system pressure variations, control pressures for load-sensing systems are sensed close to the load. These reflect only variations in that specific load, and are usually sensed at the motor port of the DCV or at a motor or actuator inlet port.

Two significant design issues arise when examining heat-dissipation in mobile applications. The first concerns the use of evolution trend prediction to establish whether or not pump control has anything further to offer in terms of reducing the root-cause heat generation problem. The second concerns the design of the heat exchanger part of the system.

Regarding the pump control evolution path, it is useful to examine the corresponding 'action co-ordination' evolution trend observed by Altshuller (Figure 10).

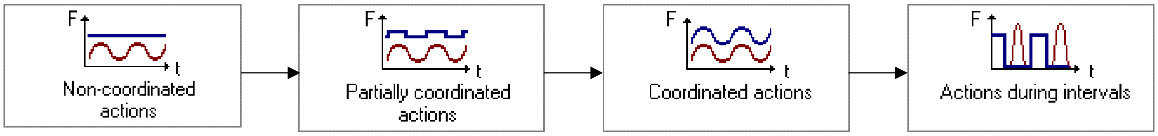


Figure 10 - *TRIZ 'Action Co-ordination' Evolution Trend*

It is clear that the pump control evolution story is consistent with the predicted trends when examining the co-ordination of the actions of the pump and it's related control valve, and the corresponding load conditions. System A represents the first step on the evolution path – in that the action of the pump is uncoordinated with the prevailing load. Systems B, C, and D each represent varying degrees of load/supply co-ordination consistent with the second evolutionary stage. Load sensing – System E – represents the third evolutionary stage – at which the load conditions and the pump/valve conditions are well co-ordinated.

The trend indicates that there is scope for further enhancement in pump efficiency, and heat generation reduction, through use of design strategies in which actions occur 'during intervals'. In the context of the pump control issue, this could either mean incorporation of some form of heat/energy store or actions to boost heat dissipation during convenient times during the duty cycle. Alternatively, looking beyond the pump control system, incorporation of a prime mover with a variable speed capability.

The other side of the heat management problem examines the design of the heat exchanger system itself. A typical mobile application would use a water-tube oil cooler. The space restrictions on most mobile applications see the creation of yet another design contradiction with respect to the design of the exchanger; where the device is required to be both compact **and** possess high effectiveness.

Similar heat exchanger contradictions have been comprehensively evaluated from the TRIZ compromise-elimination perspective *[9],* and it has been shown that significant improvements in the heat transfer rate per unit volume of heat exchanger can be achieved.

The mobile system application designer is thus presented with two equally viable design strategies; one looking at root cause heat generation issues, the other looking at compromise-eliminating heat dissipation design options. Both are equally valid. The most appropriate design strategy between the two must be made on a case-by-case basis. The decision will depend on many trade-offs involving issues like time-to-market, technical risk and other business-related issues. Alternatively an organisation might seek to examine ways to use TRIZ to address and help to eliminate these trade-offs.

Conclusions

- The growing importance of effective innovation and the ever-increasing cost of product development both mean significant increases in the responsibility borne by engineers in ensuring we achieve the ‘best’ possible solution to a problem.
- The Russian-based TRIZ inventive solving methodology offers a number of powerful new ways of looking at the design process relative to traditional ‘design is a trade-off’ assumptions. It is quite probably the most effective tool available anywhere to assist engineers in getting to that ‘right’ (compromise-free) design solution at a root-cause level.
- Problem definition is by far the most important part of the problem solving process. Altshuller’s Ideal Final Result philosophy provides a means of assisting engineers and designers in this definition process.
- The Trends of Evolution TRIZ tools provide a very powerful tool for breaking out of existing design paradigms and into new and exciting ones.
- TRIZ methods have been successfully used to derive novel leak-free coupling and connector design concepts.
- TRIZ methods have been successfully used to derive a patentable ‘self-cleaning’ filter concept design.

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Table 1 - *39 Elements of the Contradiction Matrix*

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force
11. Tension, pressure
12. Shape
13. Stability of object
14. Strength
15. Duration of action - moving object
16. Duration of action - stationary object
17. Temperature
18. Brightness
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Waste of energy
23. Waste of substance
24. Loss of information
25. Waste of time
26. Amount of substance
27. Reliability
28. Accuracy of measurement
29. Accuracy of manufacturing
30. Object affected harmful effects
31. Object generated harmful effects
32. Manufacturability
33. Convenience of use
34. Repairability
35. Adaptability
36. Complexity of device
37. Complexity of control
38. Level of automation
39. Productivity

Table 2 - *40 Inventive Principles*

1. Segmentation
2. Extraction
3. Local Quality
4. Asymmetry
5. Combination
6. Universality
7. ‘Nested Doll’
8. Counterweight
9. Prior Counter-Action
10. Prior Action
11. Prior Cushioning
12. Equi-potentiality
13. ‘The Other Way Round’
14. Spheroidality
15. Dynamics
16. Partial or Excessive Action
17. Another Dimension
18. Mechanical Vibration
19. Periodic Action
20. Continuity of Useful Action
21. Skipping
22. ‘Blessing in Disguise’
23. Feedback
24. Intermediary
25. Self-Service
26. Copying
27. Cheap/Short Living
28. Mechanics Substitution
29. Pneumatics and Hydraulics
30. Flexible Shells/Thin Films
31. Porous Materials
32. Colour Changes
33. Homogeneity
34. Discarding and Recovering
35. Parameter Changes
36. Phase Transitions
37. Thermal Expansion
38. Strong Oxidants
39. Inert Atmosphere
40. Composite Materials