FOUR STRATEGIES FOR RELIABILITY

Improving Robustness to One-sided Failure Modes

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Abstract. Reliability is one of the most important characteristics of a system. To be reliable a system must be robust – it must avoid failure modes even in the presence of the broad range of noise factors such as harsh environments, changing operational demands, and internal deterioration. In this paper we focus attention on "one-sided" failure modes, which occur only on one side of a range of noises. Four effective strategies are presented for achieving improved robustness to one-sided failure modes by conceptual improvements. Each strategy is illustrated through two examples from industrial practice.

INTRODUCTION

Reliability is the proper functioning of the system under the full range of conditions experienced in the field. The fundamental principle of reliability is *failure-mode avoidance*. Failure-mode avoidance requires two critical conditions:

1. Mistake avoidance
2. Robustness

By "mistake" we refer to the plethora of design decisions and manufacturing operations that may be grossly in error. Examples of mistakes are installing a switch backwards, or interpreting a software command as being expressed in inches when it represents centimeters. Reliability can be improved by reducing the incidence of such mistakes by a combination of knowledge-based engineering and the problem-solving process.

By "robustness" we refer to the ability of a system to function (i.e. to avoid failure) under the full range of conditions that may be experienced in the field. Conditions that may cause system failure include harsh operating environments, manufacturing variations, degradation, wide-ranging operator demands, and subsystem interface variations. The variables that define a space of operating conditions are often referred to as "noise factors" or simply "noises" (although they are not usually acoustic in nature). This paper discusses engineering approaches for making systems robust against stressful noise factors.

Robust parameter design makes systems more robust to noise factors, and has been highly developed under the leadership of Dr. Taguchi (Taguchi 1993, Phadke 1989, Fowlkes and Creveling 1995, Clausing & Fey 2004). In robust parameter design, the critical system-design variables, often referred to as control factors, are explored while simultaneously exposing the system to stressful noise conditions. By this means, it is often possible to reduce the sensitivity of the system to the noise factors. This approach is highly developed, well documented, and widely practiced (although, in the opinion of the authors, not as widely as it needs to be).

The development of robustness is most frequently done during one of four stages of system development:

1. Technology development (best practice)
2. System architecture generation and selection (best practice)
3. During detailed design (most common in current, sound engineering practice)
4. After detailed design (not recommended)
5. Downstream problem reaction (ineffective, but often practiced)

The systematic improvement in the critical functional values of selected and fixed concepts is very important, but it cannot fully account for the improvements in reliability observed in most engineering applications over long periods of time. For example, over the past several decades, there have been substantial improvements in the reliability of automobiles. Some fraction of reliability improvement is due to parameter design, which ensures that the values of critical design variables are set to appropriate values. However, many of the improvements are due to new design concepts (unibody construction), new technologies (electronic spark timing), or new configurations (e.g., multi-link suspensions). These types of innovations provide large improvements in system robustness. Engineering organizations must succeed in developing and implementing reliability-related conceptual and architectural changes to remain competitive in the long run.

The authors (Clausing 2004, Clausing and Frey 2004) recently articulated an important distinction between two-sided failure modes and one-sided failure modes. Two-sided failure modes are modes that occur at both ends of a noise factor's range. For example, temperature affects the accuracy of a strain gauge leading to unacceptably large deviations at both high and low temperatures. The failures at both ends of the range are driven by the same physical phenomenon, in this case, changes in a material's electrical conductivity. Most of traditional parameter design deals with this type of functionality.

By contrast, one-sided failure modes are modes that occur at only one end of a noise-factor's range. For example, temperature affects the flow of fuel through a pump. At high temperatures, a pump may experience vapor lock. At low temperatures, a fuel line may freeze starving a pump of fuel. In this case, the system is not subject to a single two-sided failure mode. Rather it is subject to two conflicting one-sided failure modes, each governed by distinct physical phenomena. In order to achieve reliable performance, engineers must create a sufficient operating window (Clausing 2004) between the two failure modes.

In this paper we concentrate on strategies to avoid one-sided failure modes through concept design; i.e., during system architecture and/or technology concept selection. We present four strategies for the development of robustness, each based on dual examples of actual design practices from industry:

1. Relax a constraint limit on an unconflicted control factor.
2. Use physics of incipient failure to avoid failure.
3. Create two distinct operating modes for two different demand conditions.
4. Exploit interdependence between two operating-window system variables.

To illustrate these strategies and demonstrate their versatility, we present two different example applications of each strategy, a primary example that is described in considerable detail and a brief supplementary example. Two engineering domains are used throughout (paper feeders and jet engines).

RELAX A CONSTRAINT LIMIT ON AN UNCONFLICTED CONTROL FACTOR

A control factor that affects only one of the one-sided failure modes in a system is said to be unconflicted (Clausing and Frey 2004). Such control factors should be maximized or minimized to create the greatest possible distance from the affected one-sided failure mode consistent with any constraints on the control factor. As the system is placed under greater demands over time due to system evolution or commercial competition, the operating window afforded under the current system constraints may become insufficient. Under these circumstances, the constraint can often be relaxed by making changes in the system architecture or by changes in technology. The relaxed constraint enables further changes to the unconflicted control factor which opens the operating window.

Primary Case Study – Paper Feeder. As an industrial example, we present the Xerox paper feeder that first went into production in 1981, and has appeared in many different Xerox copiers and printers. This paper feeder is known as a friction-retard feeder (Fig. 1).

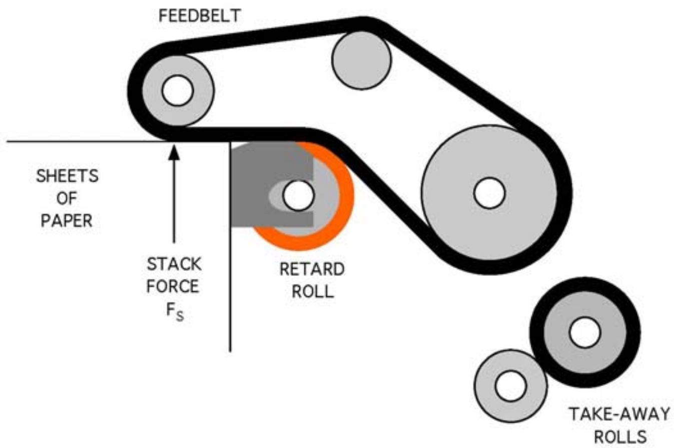

Figure 1. Friction-retard feeder.

The friction of the retard roll holds back (retards) the second sheet when it tries to come through. Thus, it prevents multifeeds (feeding of more than one sheet). Therefore, the wrap angle between the feedbelt and the retard roll only affects the failure mode of multifeeds. The other primary failure mode is misfeeds (no sheet is fed). This failure mode is not affected by the wrap angle between the feedbelt and the retard roll. Because multifeeds are reduced by a large wrap angle and misfeeds are unaffected, it is clear that the wrap angle should be as big as possible.

Despite the desirability of having a large wrap angle, the previous-generation feeder (circa 1975) had a wrap angle of only 13 degrees. In the new design that first went into production in 1981 the wrap angle was increased to 45 degrees. This large improvement in wrap angle was enabled by a change in the total system architecture. In large copiers and printers the next subsystem after the paper feeder is the registration subsystem, which aligns the sheet with the image. In the new design the architecture was changed so that the paper came out of the feeder and turned down to reach the registration subsystem (Figure 2). This enabled the wrap angle to be greatly increased. This architecture also reduced the width of the copier/printer, which is desirable. This paper feeder with the large wrap angle has been very successful in many generations of Xerox copiers and printers.

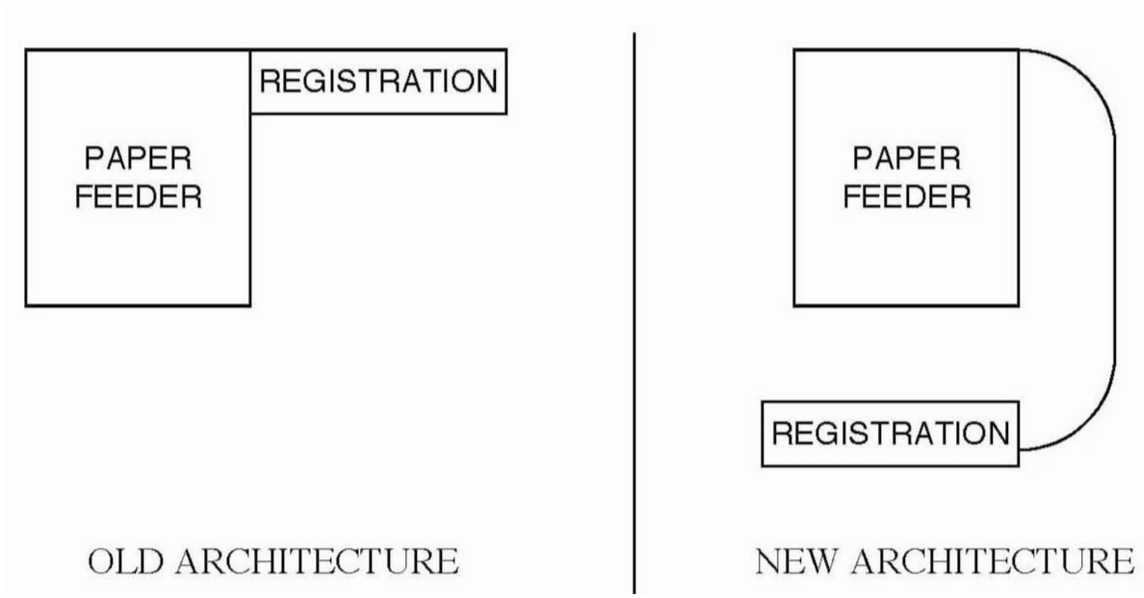

Figure 2. A new architecture enabled a larger wrap angle.

Supplementary Case Study – Jet Engines. A similar approach was used to improve the reliability of axial-flow fans in jet engines. A fan is a component of modern high by-pass commercial jet engines that provides a significant increase in the total mass flow, and therefore improvement in propulsive efficiency. A critical failure mode of such fans is flutter vibration due to the length of the blades and their exposure to inlet flow distortions. It had long been known that increasing the chord of a fan blade stiffened the blade and thereby reduced the incidence of the failure mode of flutter, but the chord of the blade was limited by constraints on weight (Koff, 2004). Eventually, new technologies for manufacturing hollow blades enabled engine manufacturers to increase chords significantly without added weight (e.g., U.S. Patent No. 4,345,877 to R. C. Monroe and U.S. Patent No. 4,720,244 to Kluppel et al.). Wide chord fans provided much greater resistance to flutter and have thereby greatly improved engine reliability. As in the case of wrap angles in paper feeders, innovation enabled a critical parameter to be pushed past its previous constraints to move a one-sided failure mode boundary and increase the operating window.

Summary of the Strategy. When a system variable only affects one of the one-sided failure modes, take its value to its constraint limit. If the operating window is still not large enough, seek new architectures or technologies that relax the constraint.

USE PHYSICS OF INCIPIENT FAILURE TO AVOID FAILURE

In some systems the physics of the incipient failure can be used to prevent or delay the failure mode. All one-sided failure modes are associated with underlying physical phenomena. In many cases the physics of the failure mode exhibit distinct physics of incipient failure – mechanisms that become active just before the onset of the failure mode. In some systems these mechanisms provide an opportunity for innovations that exploit the incipient physical mechanisms to delay failure or increase the size of the operating window.

Primary Case Study – Jet Engines. An example is afforded by the use of shaped grooves in compressor casings in modern jet engines. An axial flow compressor is comprised of multiple alternating stages of rotor assemblies and stators. To limit engine complexity and weight, a large pressure rise per stage is desired so that the desired pressure rise in the compressor can be accomplished with a small number of stages. However, the pressure increase of each stage is limited by a failure mode of aerodynamic stall and surge. A stall involves separation of airflow from a blade, which at any given time may affect only one stage or even a group of stages. A compressor surge generally refers to a complete flow breakdown throughout the compressor. The value of airflow and pressure ratio at which a surge occurs is termed the “surge point” and “surge margin” is a term for the difference between the airflow and compression ratio at which it will normally be operated and the airflow and compression ratio at which a surge will occur. Thus, we can readily interpret surge margin as the distance from the one-sided failure mode of compressor surge.

In the late 1970’s new technologies known as “casing treatments” were adopted to increase the distance from the failure mode of compressor surge. In one casing treatment technology developed by Rolls Royce, a series of angled channels are placed in the casing of the compressor extending from the leading edge of the rotors and extending just aft of the trailing edge (see Figure 3). If a small surge begins to occur, then “a rotating annulus of pressurized gas will begin to build up about the tips of the blades” (Freeman and Moritz, 1978). Because of the geometry of the slots, “the annulus of air will be directed into the slots and subsequently be exhausted from them downstream of the rotor stage back into the main gas stream flowing through the compressor thus reducing or eliminating the surge” (Freeman and Moritz 1978).

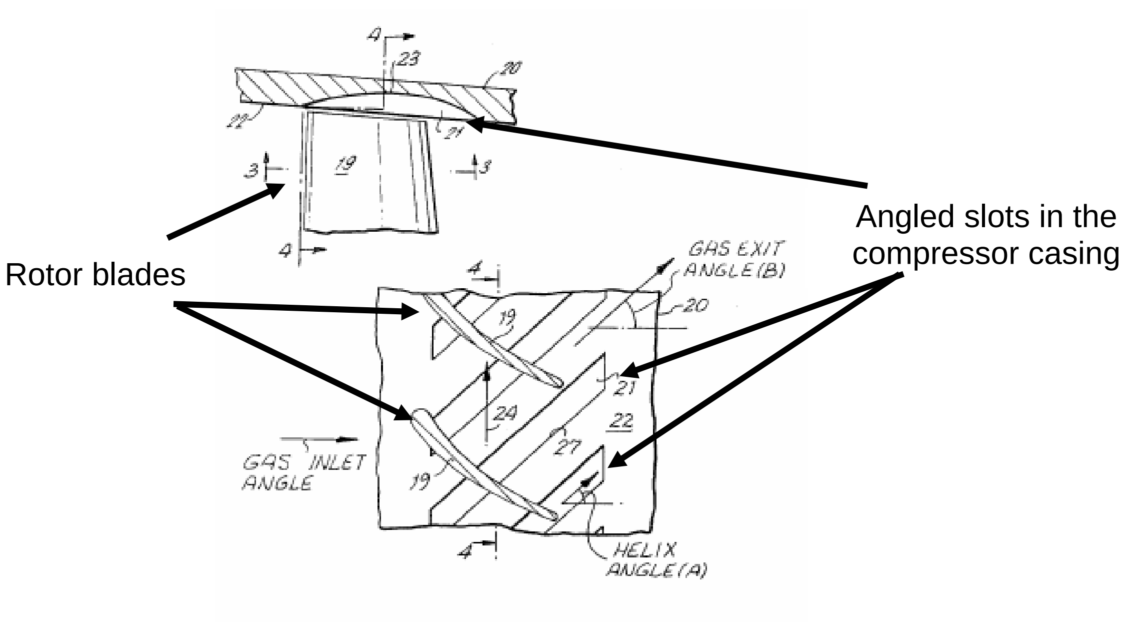

Figure 3. The arrangements of slots in an axial flow compressor.

To understand how operating window methods apply to this scenario, it is useful to sketch the parameter space and the failure mode boundaries. The left side of Figure 4 depicts the failure mode boundary for surge as typically shown in texts on engine design (e.g., Cumpsty, 1997). The mass flow in an engine may vary due to changes in inlet conditions caused by atmospheric conditions or aircraft maneuvers. This pushes the engine off the operating line and toward the failure mode boundary (the "surge line"). Before the system reaches the surge line, a rotating annulus of air forms near the tips of the compressor blade tips. This quickly evolves into a surge condition wherein the engine fails to produce thrust.

The right side of Figure 4 depicts how the the casing treatment technology described in Patent #4,086,022 changes the physical behavior of the system. Given a drop in mass flow in the engine, a rotating annulus of air begins to form. The casing treatment exploits this incipient physical mechanism to delay failure. The channeled slots in Figure 3 are arranged so that they will divert a swirling flow past the stage, thereby increasing the tip leakage flow, and lowering the pressure ratio across the compressor stage. The drop in pressure ratio associated with the drop in mass flow enables the system to stay below the surge line longer than the previous technology allowed. The net result is a "stunning improvement in surge margin of up to 20%"(Koff, 2004).

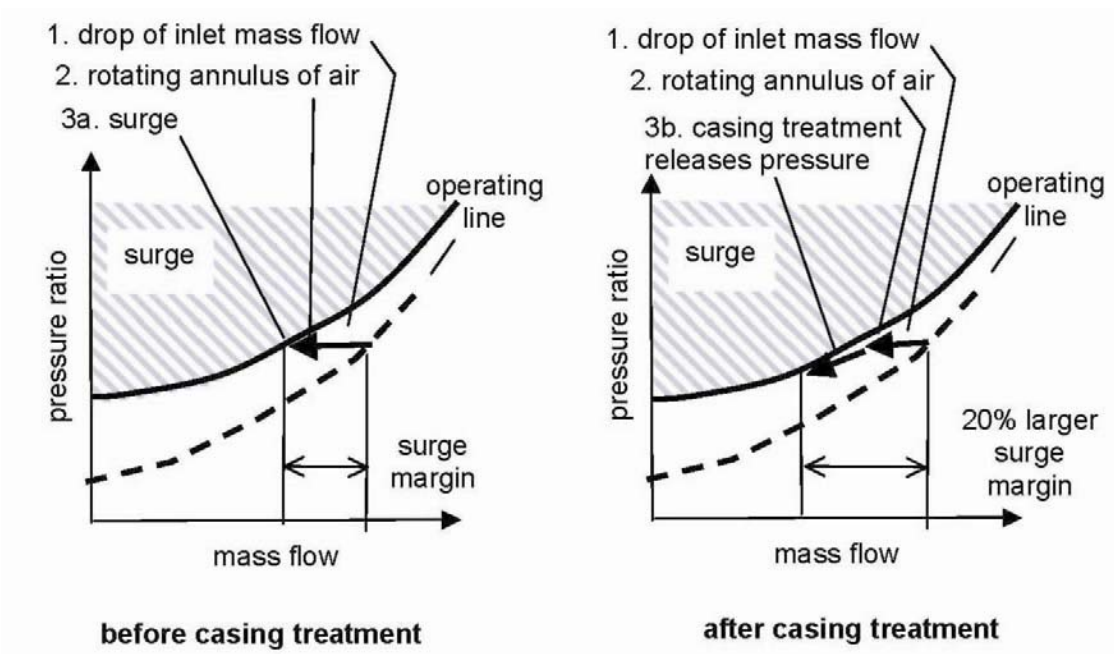

Figure 4. The effect of casing treatment on surge of jet engine compressors.

Supplementary Case Study – Paper Feeder. A similar approach was used to improve the reliability of paper feeders. For friction retard paper feeders, the stack force between the feedbelt and the paper stack is a critical system variable. If it is too large the multifeed rate will be excessive. If the stack force is too small, the misfeed rate will be excessive. Therefore, there is an operating window between these two one-sided failure modes (Fig. 5).

When the range of papers is moderate, it is easy to develop a sufficient operating window so that both the multifeed rate and the misfeed rate are very small. However, for the large range of papers that are typically used in large production copiers and printers, it is very difficult, or impossible, to develop a sufficient operating window, as shown on the left of Figure 5.

On the left hand side of Figure 5, it is evident that no single value of stack force will simultaneously avoid both multifeeds and misfeeds over the full range of paper weights.

This was still true after robust parameter design had been completed, so there was little hope to improve it further beyond the great improvement that had already been achieved.

The problem was resolved through the development of a "stack force relief/enhancement" technology (US Patent # 4,475,732, Clausing et al., 1982). This technology uses two different values of the stack force, a small value for most paper, and a larger value for heavy papers (as depicted on the right side of Figure 5). Under normal conditions, the stack force is set to the small value. For most common paper weights this works very reliably. If a larger paper weight is used, a misfeed condition may begin to emerge. A sensor near the retard roll is designed to sense the arrival of the lead edge of the sheet. If an incipient misfeed occurs, the paper will not arrive within the desired time period. Under this condition, the stack force is increased to the large value. Thus, the machine was able to reliably feed the full range of paper weights.

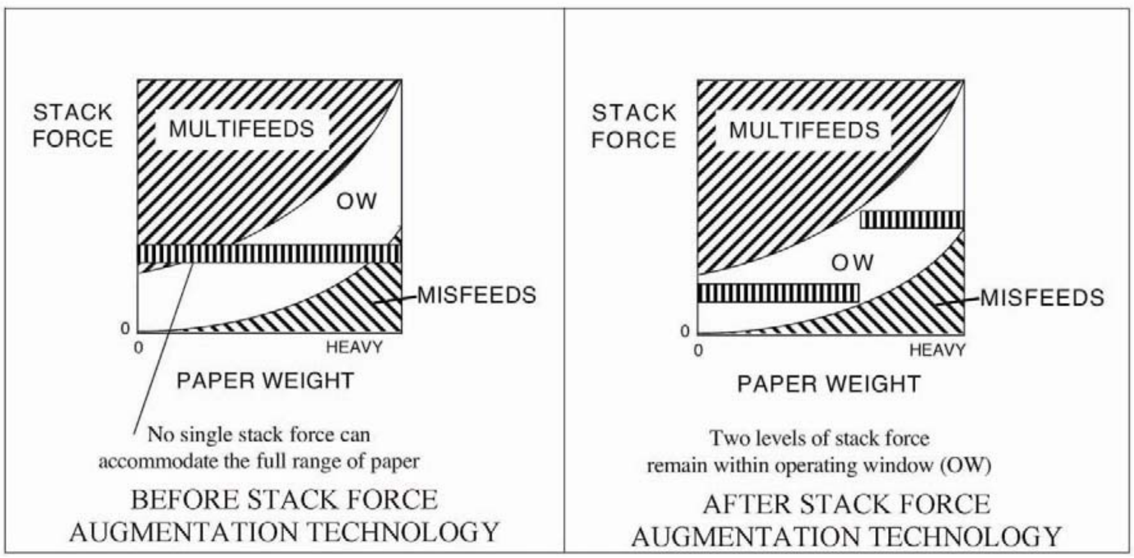

Figure 5. Operating window for friction retard paper feeder.

Summary of the Strategy. Exploit the physical mechanisms associated with an incipient failure to offset the failure mode thereby increasing size of the operating window.

EMPLOY TWO DIFFERENT OPERATING MODES

In some cases, the development process reaches a state in which the system has a limited operating window between multiple one-sided failure modes and therefore cannot operate reliably. In such cases, it is often advisable to change from a single operating mode to two operating modes. Separately designing two distinct operating modes enables significant design freedom to seek better resistance to the failure modes. This strategy is often similar to the strategy "use physics of incipient failure to avoid failure" and in fact the two strategies can overlap. However two key distinctions should be made: 1) incipient failure mode physics do not always lead to clearly distinct operating modes, and 2) the switch between two modes need not be cued by incipient failure physics and can instead be cued by operator inputs or state variables of the system.

Primary Case Study – Paper Feeder. A failure mode of friction retard paper feeders (Figure 1) is excessive wear of the retard roll. In previous designs the roll had been rotated approximately once per hour to distribute the wear over the entire roll.

Nevertheless the wear was excessive, and was a considerable expense in service cost and lost production of the copier/printer.

The critical variable that determines the wear of the retard roll is the force between the feedbelt and the retard roll, F, multiplied by the contact distance, D, between the feedbelt and the retard roll. The product, FD, is the work that the retard roll can do to remove energy from the second sheet, and thus stop the second sheet. However, this is also the work that causes wear of the retard roll.

The result is as shown in Figure 6. With the previous design, one system variable FD has control of both of the one-sided failure modes, excessive multifeeds and excessive wear of the retard roll. An engineer at Xerox recognized that this problem could be resolved through a redesign of the retard mechanism by adding a second operating mode. The innovation is described in US Patent 4,475,732 and was included in the advanced paper feeder that first went into production in the Xerox 1075 copier in 1981.

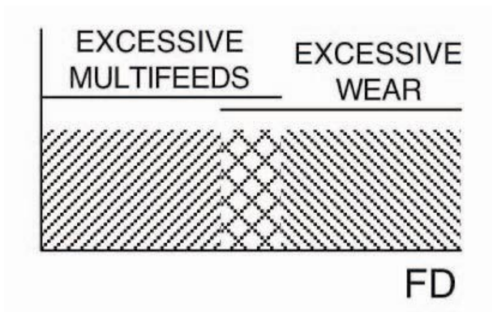

Figure 6. Two failure modes, one system variable.

The inventive process that led to US Patent 4,475,732 is well described in terms of the theory of inventive problem solving (TRIZ). The TRIZ process generally begins by framing the current problem as a conflict. In this case, there was an engineering conflict between avoiding multifeeds and avoiding excessive wear. In TRIZ, one effective way to seek a conflict resolution is through "Sufield" or substance-field analysis" (Clausing & Fey 2004). Simple Sufield diagrams are in the form of a triad. The relevant triad diagram for the retard-roll problem is shown in the left hand side of Figure 7. Here substances are (1) the paper and (2) the roll/shaft. The field is the contact force. TRIZ includes many standards for the creative revision of the Sufield. One of the standards is: "To enhance the effectiveness of the Sufield, transform one substance into an independently controlled Sufield, thus generating a chain Sufield." This can be implemented by introducing a field between the retard roll and its shaft (as shown in right hand side of Figure 7).

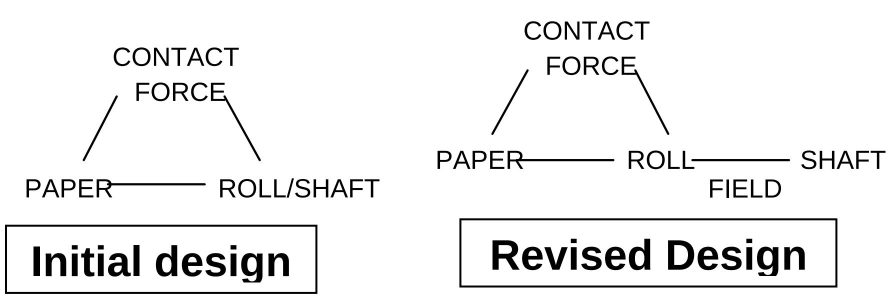

Figure 7. Sufield diagrams for retard roll.

This is as far as Sufield analysis will take us. Now we have to use science and art to identify a field and a component for creating the field that will open an operating window. One such approach is to insert a friction brake with a brake torque T into the design to produce a field between the retard roll and its shaft (US Patent 4,475,732). This field creates the possibility of two distinct operating modes: (1) when the torque that is applied to the roll is less than T, the roll remains stationary, and (2) when the torque that is applied to the roll is greater than T, the roll rotates.

The torque that is applied to the retard roll is produced by the friction from the belt or the paper, whichever is contacting the roll. When one sheet of paper is between the roll and the feedbelt, the friction coefficient is 2, which overcomes the brake torque. Therefore, the roll rotates, and there is not any wear. When two sheets of paper are between the roll and the feedbelt, the friction coefficient is 0.6, and the brake torque prevents rotation of the retard roll. Thus the second sheet is stopped.

The addition of the new operating mode created an additional design parameter “brake torque” which sets the condition for the switch between the two modes. Thus, the design space expands from a 1-D operating window to a 2-D operating window (Fig. 8). If the brake torque is set to an appropriate value, the retard roll will only rub against the paper when the incipient multifeed condition actually occurs. In this case, the excess wear failure mode boundary is never active and a new failure mode (paper damage) becomes the limiting factor on parameter FD, leaving a greatly increased operating window.

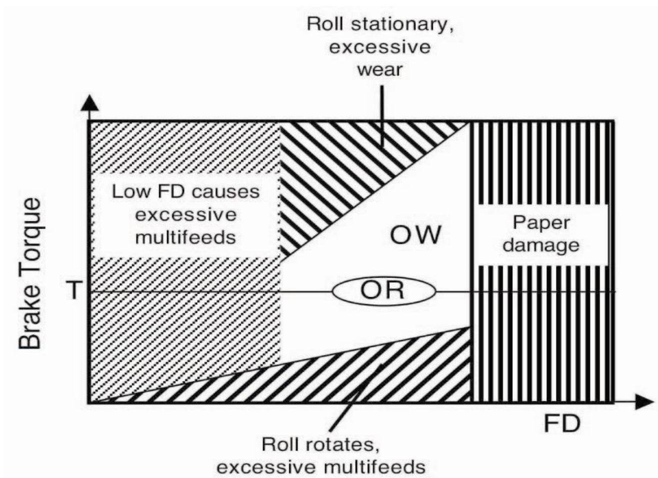

Figure 8. Two-dimensional operating window (OW) with included operating region (OR) for improved retard-roll design.

Supplementary Case Study – Jet Engines. A similar approach was used to simultaneously avoid two one-sided failure modes associated with combustion in jet engines. A combustor is a part of a jet engine in which fuel is injected into the air stream, mixed with air, and burned. Two key failure modes of a combustor are concerned with the composition of the exhaust gas, which is tightly regulated to protect the environment. One failure mode is excessive production of carbon monoxide (CO), which occurs with an overly lean mixture and low temperature in the combustion zone. Another failure mode is excessive production of oxides of nitrogen (NOX), which is associated with overly high temperature in the combustion zone. Given the changes in the thrust demands, (and many other parameters that vary) it is a challenge to maintain the combustion conditions in the small operating window between the failure modes. In the 1970's a new technology called "two-zone" or "staged" combustion substantially increased the operating window by affording multiple operating modes (Lefebvre, 1999). When the demand for thrust is low, all the combustion takes place in a single "primary zone". When thrust demands are highest, the engine automatically switches to a mode in which combustion occurs in two different zones, each of which is functioning within the operating window between the CO and NOX related failure modes. As in the case of the paper feeders with a friction brake, the system automatically switches between two modes of operation in order to increase the operating window between two conflicting one-sided failure mode boundaries.

Summary of Strategy. When it is not possible to simultaneously avoid two one-sided failure modes due to a wide range of noise values, consider defining two distinct operating modes so that at least one of the failure modes will be moved away from the operating range.

IDENTIFY AND EXPLOIT DEPENDENCIES AMONG FAILURE MODES

In the operating window approach, the parameter space is sketched out and the failure mode boundaries are identified. In the sketch, it is often the case that the parameters associated with the axes are not independent. A small change induced in one parameter will have an associated effect on the other one. It seems clear that such dependencies can influence system reliability. What is sometimes overlooked is that they often provide an opportunity to use the dependence to stay within the operating window.

Primary Case Study – Jet Engines. An example is afforded by turbine blade cooling systems [Sidwell, 2004]. The physical layout of the system is described in Figure 9. Air from the compressor is routed to the first stage turbine blades. The cooling flow path includes a Tangential On-Board Injector, which brings the flow from a supply at Ps into the rotating parts of the engine. The area between the rotating seal and the blades acts as a plenum storing compressed gas at a pressure Pp. The gas then flows through each of the many first stage blades. The purpose of this flow is to cool the surface of the blades and thereby avoid the failure mode of early blade oxidation.

To apply operating window methods to this scenario, one may first sketch the parameter space and the failure mode boundaries. Figure 10 depicts a highly simplified window with just two failure modes, oxidation of blade #1 and oxidation of blade #2. Manufacturing variation may excite failure mode #1 (oxidation of blade #1) if its flow passages are constricted causing m1 to drop. However, the schematic diagram of Figure 10 suggests that there is a dependency among the failure modes. Any small drop in m1 tends to cause a rise in plenum pressure and a resulting rise in m2. The reverse is also true -- any small drop in m2 tends to cause a rise in plenum pressure and a resulting rise in m1. This interdependency of the failure modes creates an opportunity to create larger distance from both failure modes. Turbine blades are routinely tested for their flow characteristics. Sidwell proposed that this test could be used to sort the blades into low flow, medium flow, and high flow classes. In this way, a second interdependency is added to the system. The low m1 due to the sorting process brings about a low m2. The nature of the interdependency caused by the plenum causes the two effects to cancel (or very nearly cancel) as depicted in Figure 10. Sidwell estimated that "binning" turbine blades will increase the life of the high flow and medium flow blades by 50% or more and would enable low flowing blades to be used with approximately the same life as current engines.

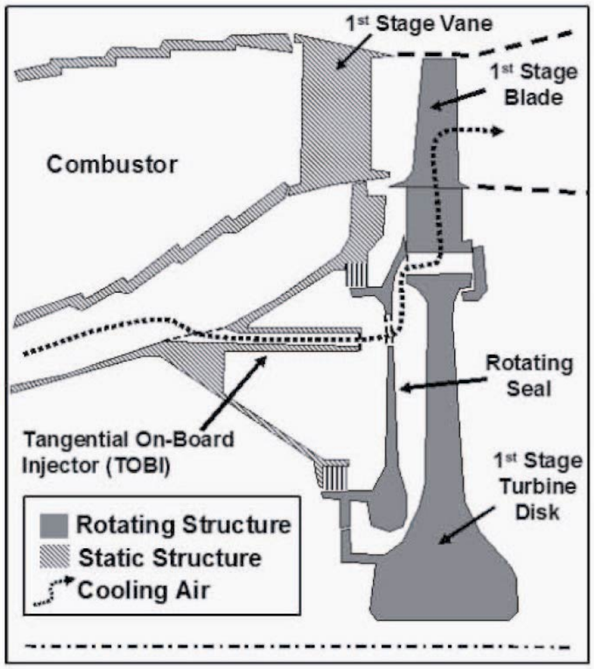

Figure 9. Physical layout of a cooling system for a turbine blade.

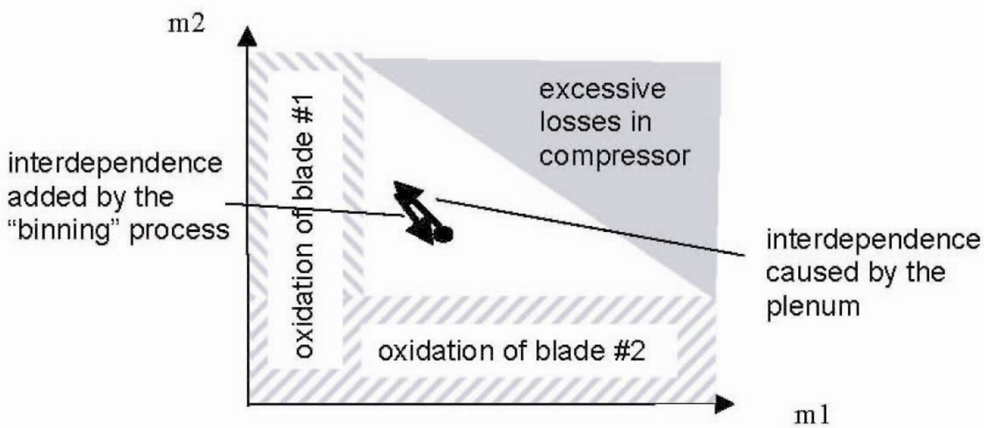

Figure 10. The failure mode boundaries in a simplified, two-blade system.

Supplementary Case Study – Paper Feeder. In a document feeder for a copier it is highly desirable to feed from the bottom of the stack of documents. This leaves the top of the stack free to receive the recirculated document after it has been copied.

The best document-feeder technology uses air to move the document. That minimizes any possible damage to the document. Such feeders typically use a combination of positive air pressure and negative air pressure (vacuum).

The positive air pressure is used to levitate the document stack. Otherwise the weight of the document stack would tend to cause both misfeeds and multifeeds. Therefore, a sufficient pressure under the stack is required to avoid both misfeeds and multifeeds. However, excessive pressure under the stack could cause the last sheet to blow away. Therefore, good system design requires an operating window (OW) between inadequate pressure and excessive pressure, as shown in Figure 11.

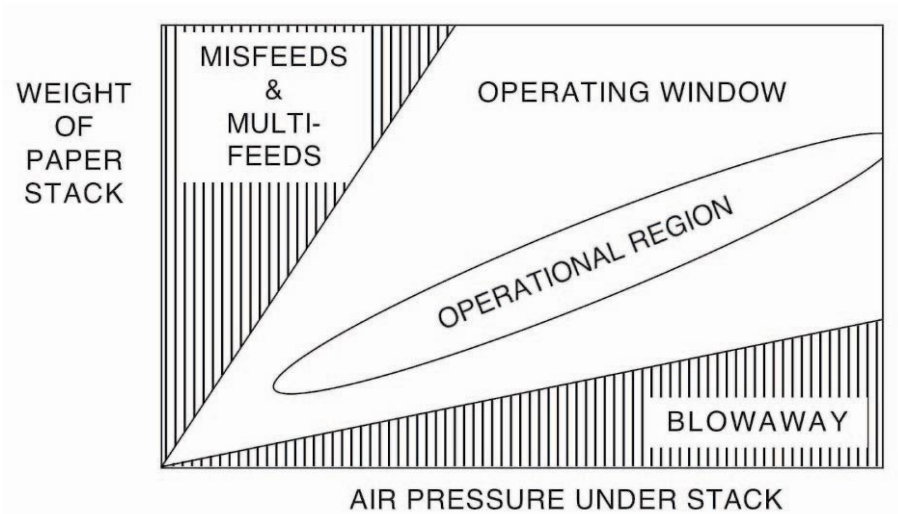

Figure 11. Operating window for bottom-feeding vacuum document feeder.

The simple approach to achieve robust document feeding is to arrange a natural dependence between weight of the paper stack and the air pressure under the stack. This is done by careful sizing of all of the flow impedances. Thus the pressure under the stack is maintained proportional to the stack weight without the need for any additional components. This strategy was used in U. S. Patents 4.014.537, 4,275,877, and 4,411,417, which are successive improvements that make the technology more robust.

Summary of the Strategy. When there are interdependencies among failure modes, look for ways to use those dependencies to counteract the effects of noise factors.

SUMMARY

Four strategies for the industrial achievement of robust reliability have been presented. They apply to one-sided failure modes, and improve robustness by better technological concepts and improved system architectures. Here we have presented case studies from paper feeders and jet engines for each strategy.

The four strategies are:

1. Relax a constraint limit on an unconflicted control factor. When a system control factor affects only one one-sided failure mode, then it should be taken as far as possible in the direction of turning off the failure mode. Often the previously existing constraint can be moved during the System Architecture phase to enable further improvement of robustness.

2. Use physics of incipient failure to avoid failure. Failure modes usually do not occur with a step function in the physical behavior. Instead there is a buildup to the failure occurrence. Sometimes this change in the physics can be utilized to avoid the actual occurrence of the failure mode.
3. Create two distinct operating modes for two different demand conditions. This often involves the addition of a component (and corresponding system control variables) so that the system can adapt itself to differing conditions.

Exploit interdependence between two operating-window system variables. When the operating window lies at an angle in a 2-D functional space, then dependence between the two operating-window variables can be exploited to keep the operating point within the operating window.

REFERENCES

Clausing, Don, and Daniel D. Frey. (2004) "Failure Modes and Two Types of Robustness." INCOSE Annual Symposium.

Clausing, Don, and Victor Fey. (2004) *Effective Innovation*. New York: ASME Press.

Clausing, Don. (2004). "Operating Window–An Engineering Measure for Robustness,"*Technometrics* 46 (1): 25-29.

Cumspsty, 1997, *Jet Propulsion: A Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines*, Cambridge University Press, Cambridge, UK.

Fowlkes, William Y., and Clyde M. Creveling. (1995). *Engineering Methods for Robust Product Design*. New York: Addison-Wesley.

Freeman, C., and R. R. Moritz, 1978, "Gas turbine engine with improved compressor casing for permitting higher air flow and pressure ratios before surge", U. S. Patent 4086022.

Koff, B. L., 2004, "Gas Turbine Technology Evolution: A Designer's Perspective", *AIAA Journal of Propulsion and Power* 18 (14) 577-595.

Lefebvre, A. H, 1999, *Gas Turbine Combustion*. Taylor & Francis, Philadelphia, PA.

Markowski, S. J., R. P. Lohmann, and R. S. Reilly, R. S., 1975, "Vorbix burner: A new approach to gas turbine combustors," American Society of Mechanical Engineers, n 75-GT-20.

Phadke, Madhav. (1989). *Quality Engineering Using Robust Design*. Englewood Cliffs, NJ: Prentice Hall.

Sidwell, C. V., 2004, "On the impact of variability and assembly on turbine cooling flow and oxidation life", Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Taguchi, Genichi. (1993), *Taguchi on Robust Technology Development*. New York: ASME Press.

BIOGRAPHIES

Don Clausing worked in industry for 29 years before becoming a half-time faculty member at MIT from 1986 until 2000. Starting about 1975 he has had a role in the major improvements in product development and systems engineering that have enhanced the competitiveness of many commercial industries. This includes the publication (1993) of his book Total Quality Development – World-Class Concurrent Engineering. He now has a new book (2004), co-authored with Victor Fey, Effective Innovation – The

Development of Winning Technologies. Clausing has long been a leader in robust design, a key to reliable systems.

Dan Frey conducts research and teaches in the areas of design methodology, statistics, and systems engineering. He currently holds a dual key faculty position at MIT in the Department of Mechanical Engineering and in the Engineering Systems Division.