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The Alaska Airlines Flight 261 Accident: a Systemic Analysis of Functional Resonance

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On January 31, 2000, Alaska Airlines flight 261, an MD-83, crashed into the Pacific Ocean; after airplane pitch control was lost as a result of the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads (NTSB, 2003). Accident investigation revealed a wide range of human, technical, and organizational factors contributing to this tragic event, providing a case where popular linear models and methods have difficulty addressing the full complexity of the processes leading up to the accident. This paper treats each of the steps of analysis according to the Functional Resonance Accident Model (FRAM; Hollnagel, 2004), a systemic non-linear modeling method, and discusses how functional resonance occurred through the variability in functions performed by joint human, technical, and organizational systems. It thereby aims to facilitate a better understanding of how functional variability in design, certification, limited and inadequate maintenance, negligent safety culture, economic factors, and human performance together can resonate and contribute to accidents. In this way it aims to contribute to accident prevention and the engineering of more resilient complex dynamic systems.
Alaska Airlines Flight 261

The stabilizer of the MD-80 series consists of a horizontal pivoting wing mounted on top of the vertical tail fin of the aircraft. The horizontal stabilizer directs the pitch (nose-up/-down) of the aircraft. The horizontal wing rotates around the horizontal stabilizer aft hinge point at the back of the horizontal stabilizer, so that if the front of the horizontal stabilizer is down, it presses the tail down, and thereby the nose of the airplane up. The back edge of the horizontal stabilizer is the elevator, which the (auto-) pilot uses to control the aircraft pitch. The whole horizontal stabilizer can be trimmed to set the wings to a ‘default’ air flow so that the nose pitch can be adjusted to the centre of gravity of the aircraft. The horizontal stabilizer and its trim tabs can be controlled by the autopilot, and by the pilot with the flight controls and switches in the cockpit. This helps the pilots because it makes the controls lighter to handle, and by adjusting the trim the pilots do not need to pull or push the control column to compensate for a centre of gravity that has moved to the front or to the back because of the aircraft’s changing load.

A jackscrew assembly at the front of the horizontal stabilizer moves the front of the horizontal wing up and down. Inside the front of the vertical stabilizer attached to the horizontal stabilizer front spar attach bracket there are two motors (primary and alternate) rotating an acme screw. This screw rotates in an acme nut that is attached to the vertical stabilizer, thus moving the horizontal stabilizer up and down. The screw and the nut both have two threads each. There are both electrical and mechanical stops (the latter at more outward positions than the former) to prevent the screw from rotating beyond a certain point. Beyond a certain horizontal stabilizer position, the elevators cannot compensate for the upward or downward pressure of the stabilizer. There are maximum downward and maximum upward positions for the horizontal stabilizer, ensuring that the (auto-) pilot can still control the pitch of the aircraft with the elevators. Furthermore, the threads on screw and nut need to be lubricated to avoid excessive wear. This wear is checked during so-called end-play checks, where an inspector and a mechanic check the possibility for movement between screw thread and nut thread, which is a direct measurement for wear.

The executive summary of the National Transportation Safety Board's accident report gives an outline of the probable causes of the accident in the eyes of the NTSB:

“The National Transportation Safety Board determines that the probable cause of this accident was a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines' insufficient lubrication of the jackscrew assembly. Contributing to the accident were Alaska Airlines' extended lubrication interval and the Federal Aviation Administration's (FAA) approval of that extension, which increased the likelihood that a missed or inadequate lubrication would result in excessive wear of the acme nut threads, and Alaska Airlines' extended end play check interval and the FAA's approval of that extension, which allowed the excessive wear of the acme nut threads to progress to failure without the opportunity for detection. Also contributing to the accident was the absence on the McDonnell Douglas MD-80 of a fail-safe mechanism to prevent the catastrophic effects of total acme nut thread loss.”

(NTSB, 2003, p. xii)

The Functional Resonance Accident Model

The functional resonance model (Hollnagel, 2004) describes system failure as a resonance of the normal variability of functions. To arrive at a description of functional variability and resonance, and to determine recommendations for damping unwanted variability, a FRAM analysis consists of four steps:

Step 1

Identifying essential system functions, and characterizing each function by six basic parameters.

Functions are described through six aspects, in terms of their input (I, that which the function uses or transforms), output (O, that which the function produces), preconditions (P, conditions that must be fulfilled to perform a function), resources (R, that which the function needs or consumes), time (T, that which affects time availability), and control (C, that which supervises or adjusts the function), and may be described in a table and subsequently visualized in a hexagonal representation (FRAM module, Figure 1).

Step 2

Characterizing the (context dependent) potential variability through common performance conditions.

Eleven common performance conditions (CPCs) are identified in the FRAM method to be used to elicit the potential variability: 1) availability of personnel
and equipment, 2) training, preparation, competence, 3) communication quality, 4) human-machine interaction, operational support, 5) availability of procedures, 6) work conditions, 7) goals, number and conflicts, 8) available time, 9) circadian rhythm, stress, 10) team collaboration, and 11) organizational quality. These CPCs address the combined human, technological, and organizational aspects of each function. After identifying the CPCs, the variability needs to be determined in a qualitative way in terms of stability, predictability, sufficiency, and boundaries of performance.

**Step 3**

Defining the functional resonance based on possible dependencies/couplings among functions and the potential for functional variability.

The output of the functional description of step 1 is a list of functions each with their six aspects. These functions may be linked together through their aspects. For example, the output of one function may be an input to another function, or produce a resource, fulfill a pre-condition, or enforce a control or time constraint. When the links between functions are found, through thorough analysis of functions and common or related aspects, these links may be combined with the results of step 2, the characterization of variability. That is, the links specify where the variability of one function may have an impact, or may propagate. This analysis thus determines how a (stochastic) resonance can occur of variability across functions in the system. For example, if the output of a function is unpredictably variable, another function that requires this output as a resource may be performed unpredictably as a consequence. Many such occurrences and propagations of variability may have the effect of resonance; the added variability under the normal detection threshold becomes a 'signal', a high risk or vulnerability.

**Step 4**

Identifying barriers for variability (damping factors) and specifying required performance monitoring.

Barriers are hindrances that may either prevent an unwanted event to take place, or protect against the consequences of an unwanted event (Hollnagel, 2004). Barriers can be described in terms of barrier systems (the organizational and/or physical structure of the barrier) and barrier functions (the manner by which the barrier achieves its purpose). In FRAM, four categories of barrier systems are identified (each with their potential barrier functions, see Hollnagel, 2004):

1. Physical barrier systems block the movement or transportation of mass, energy, or information. Examples include fuel tanks, safety belts, and filters.
2. Functional barrier systems set up pre-conditions that need to be met before an action (by human and/or machine) can be undertaken. Examples include locks, passwords, and sprinklers.
3. Symbolic barrier systems are indications of constraints on action that are physically present. Examples include signs, checklists, alarms, and clearances. Potential functions encompass preventing, regulating, and authorizing actions.
4. Incorporeal barrier systems are indications of constraints on action that are not physically present. Examples include ethical norms, group pressure, rules, and laws.


Besides recommendations for barriers, FRAM is aimed at specifying recommendations for the monitoring of performance and variability, to be able to detect undesired variability. Performance indicators may thus be developed for every function and every link between functions.

**FRAM Applied to Alaska 261**

The first step involves identifying essential system functions, and characterizing each function by six basic parameters. By going through the events and activities through time and throughout the socio-technical system, as reported in the accident report (NTSB, 2003), functions may be identified to form a description of the essential system functions. Functions are described through their aspects, which have also be extracted from the accident report or other sources of information. In the Alaska 261 case the report contains
considerably detailed information so that a functional account of the performance of the socio-technical system may be established. Table 1 presents an example, the function of 'end-play checking'.

<table>
<thead>
<tr>
<th>End-play checking</th>
<th>Aspect description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Jackscrew system</td>
</tr>
<tr>
<td></td>
<td>End-play check form</td>
</tr>
<tr>
<td>Output</td>
<td>Checked jackscrew</td>
</tr>
<tr>
<td></td>
<td>End-play form filled</td>
</tr>
<tr>
<td>Preconditions</td>
<td>Aircraft available for maintenance</td>
</tr>
<tr>
<td>Resources</td>
<td>Manpower</td>
</tr>
<tr>
<td></td>
<td>End-play check equipment</td>
</tr>
<tr>
<td>Time</td>
<td>Mechanics' other duties</td>
</tr>
<tr>
<td>Control</td>
<td>End-play check procedures</td>
</tr>
<tr>
<td></td>
<td>Alaska Airlines inspections</td>
</tr>
<tr>
<td></td>
<td>FAA inspections</td>
</tr>
<tr>
<td></td>
<td>FAA interval approvals</td>
</tr>
</tbody>
</table>

Table 1. A FRAM module function description.

Many such functions may be described, as will be illustrated further on. Note that there is no single right level of analysis, but the analysis continues until the analyst decides the granularity of the analysis to be fine enough to account for the variability in system behavior that needs to be explained.

In step two (context dependent) potential variability is characterized through common performance conditions (CPCs). In the case of a prospective (risk) analysis of a system this would mean the characterization of variability ranging from normal situations to worst case scenarios. In this case of retrospective analysis of an accident report, the specific scenario and data for which to determine the potential variability are given. Table 2 presents an example of the CPCs for the function 'end-play checking'.

<table>
<thead>
<tr>
<th>End-play checking</th>
<th>Performance conditions</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avail. (person, eq't)</td>
<td>Understaffing</td>
<td>Inadequate</td>
</tr>
<tr>
<td>Training/prep./comp.</td>
<td>Adequate</td>
<td></td>
</tr>
<tr>
<td>Comm quality</td>
<td>Unclear rules/indications</td>
<td>Ineffective</td>
</tr>
<tr>
<td>HMI, ops support</td>
<td>Clumsy equipment</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Avail (procedures)</td>
<td>Unclear procedures</td>
<td>Inappropriate</td>
</tr>
<tr>
<td>Work conditions</td>
<td>Lax safety culture</td>
<td>Incompatible</td>
</tr>
<tr>
<td>#Goals &amp; conflicts</td>
<td>Efficient &amp; thorough</td>
<td>&gt; Capacity</td>
</tr>
<tr>
<td>Available time</td>
<td>Time pressure</td>
<td>Inadequate</td>
</tr>
<tr>
<td>Circadian rhythm</td>
<td>Adjusted</td>
<td></td>
</tr>
<tr>
<td>Team collaboration</td>
<td>Overruling checks</td>
<td>Inefficient</td>
</tr>
<tr>
<td>Organization quality</td>
<td>Bureaucracy, no feedback</td>
<td>Ineffective</td>
</tr>
</tbody>
</table>

Table 2. End-play checking CPCs.

In case of the end-play checking function, the accident report states that there was a high pressure on maintenance personnel at Alaska Airlines, affecting the availability of personnel and time. Furthermore, there were unclear indications of how serious an end-play exactly at the regulatory allowable limit would be, even at the before-last check where this was the case. Also, the equipment with which this was done was difficult to use, and the procedures unclear. The measurement was subsequently verified and the measurement decision overruled by a maintenance team member, who measured a lower end-play and chose this safer result to be final. In general, the reported interviews with personnel indicate occurrence of efficiency-thoroughness trade-offs (Hollnagel, 2004) with statements like ‘it's not really important’, ‘this is normally OK’, and ‘it will be checked by someone else later’, indicating a rather lax safety culture. As a last example, many steps through the managerial levels at Alaska Airlines, review boards, and the FAA were necessary in order to change the end-play check intervals, steps that after the fact proved to be ineffective.

The third step defines the functional resonance based on possible dependencies/couplings among functions and the potential for functional variability. We will illustrate this process by taking up a few examples of contributing factors as identified by the accident report (NTSB, 2003).

As an example we may sketch how the two maintenance functions of 'lubrication' and 'end-play checking' are linked to the function 'maintenance oversight', as sketched in Figure 2. The regulator, the FAA, performs oversight of the maintenance at airlines. This can be described as a function, which is also constrained in available time for instance. The function 'lubrication' may be defined similarly to 'end-play checking', these functions have similar aspects. Then the output of the 'maintenance oversight' function is the control on the two maintenance functions. This means that the variability that occurs in maintenance oversight makes that the control of the maintenance functions vary. If the controls of these functions have high variability, the performance of these functions will also have variability.

This then again resonates with variability in other functions in the system. As is sketched in Figure 3, a variability in the output of 'end-play checking' and 'lubrication' links to a variability in the functioning of the jackscrew system, and therefore in the control of the horizontal stabilizer, and aircraft pitch control.
Figure 2. The functions 'end-play checking', 'lubrication', and 'maintenance oversight' and links between them, with specifications and indications (red/dark) of undesired variability.

Figure 3. Functions in normal situations, and links between functions. Aspects with undesired variability contributing to the accident are indicated in red (dark), lacking links and functions by dashed lines.
Thus we can see that the variability that is identified by CPCs in various functions may have consequences for other functions, a process which is traceable through matching function aspects. In this sense, the variability of several functions may resonate in that the variability adds up to an overall system performance that is beyond the envelope of safe functioning. A 'signal' in the form of an accident may emerge.

Many more examples from this intriguing accident could be presented in terms of function descriptions, variability analyses, links between functions, and emergence of resonance, if paper size constraints would allow. For more details about the accident please refer to the NTSB (2003) report or Dekker's (2004) analysis.

The fourth step includes (1) identifying barriers for variability that are designed to dampen undesired variability, and (2) specifying required performance monitoring to allow for necessary variability while being able to detect when this variability is undesired.

Here, divergence between the system as it was designed and envisioned, as it functions in practice, and as it with hindsight ought to have functioned and been designed, may be found. In order to dampen the variability in control of both maintenance functions in Figure 2 for example, the regulating symbolic barrier of the procedure may be strengthened (the procedure made more clear) so that the barrier system (procedure) will have its desired effect and the end-play checking function is performed with less variability. The function 'limiting stabilizer movement' (Figure 3) is an example of a design flaw. A restraining physical barrier on horizontal stabilizer movement may have provided the failsafe mechanism that was judged not to be in place in the design of the MD-80 (or its predecessor, the DC-9, originally). To summarize, the FRAM barrier vocabulary enables the specification of damping factors where undesirable variability is expected or detected. The second effort in safety management is therefore the monitoring of variability and the examination of when this variability is undesired.

This constitutes the second part of step four, specifying performance indicators to enable monitoring of variability. As an example, the 'maintenance oversight' function. At the time of the accident, and after a series of apparently locally rational increments, the maintenance intervals of lubrication and end-play checking were several times larger than the intervals prescribed in the sixties for the DC-9. The question is how to be able to foresee which variability may safely occur in order to cope with a competitive transport market, and which variability to dampen. Performance indicators based on an extensive analysis of sources of variability and links between functions may aid in making these decisions.

**Conclusion**

This paper describes and applies the Functional Resonance Accident Model to a retrospective analysis of failure of a complex socio-technical system, in order to highlight the dynamics of these systems with regard to non-linear interdependencies and variability in function performance, and to sketch FRAM's unique systemic perspective of functional resonance. The paper argues that FRAM is able to capture the dynamics and non-linearities that non-systemic models have difficulty explaining. Future empirical studies of prospective analyses are suggested to test the model and accompanying method to be able to evaluate FRAM's full potential.

**References**


