Introduction of the Concept of Functional Resonance in the Analysis of a Near-Accident in Aviation.

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The analysis of complex events shows that the performance of crew members and/or air traffic controllers, as well as the aircraft and its systems, may vary within different time frames. Thus, the understanding of the current situation can differ significantly within the crew and between the cockpit and the ground, as well as be at odds with the aircraft's real position and attitude over time. Further, these components interact throughout the flight.

This paper presents a proposal for how better to model these complex interdependencies, using the principles of the Functional Resonance Accident Model (FRAM). The outcomes of this modelling can conveniently be shown by means of open source software, the FRAM Visualizer.

Using an incident initiated where the Captain selected the wrong HSI track, we explore the many factors that influenced the situation when the crew put the aircraft into descent but failed to intercept the localizer. This led to a crisis that they had to manage, departing significantly from Standard Procedures, and without being fully aware of their proximity to the ground when they initiated a go-around.

Our aim is to develop new analytical tools in order to better characterize and understand how the flight evolved beyond acceptable safety margins, and how the crew recovered from a critical situation. Some of the factors and their comparative interactions identified in this manner may reveal inherent risks that are still present but also preventable.

Keywords: Functional resonance analysis, aircraft accident investigation,

The BEA investigated an incident that occurred on 23 November 1997 on approach to Paris-Orly to the MD83 registered F-GRMC. A final report[1] was issued at the time. It was determined that the incident resulted from the decision to put the aircraft into descent when, as a result of a display error, it was neither on the localizer track nor on the glide path, and with no context defined for this improvised manoeuvre. The operator's company culture directly contributed to the incident through the importance it attached to accelerated training given to new First Officer and to undertaking commercial flights. Ten years later, a re-

[1] The final report on this event is available on www.bea.aero

analysis using functional resonance methods provides a better characterisation of the evolving circumstances in which the crew actions took place.

1. The Functional Resonance Accident Model

The functional resonance accident model (FRAM; Hollnagel, 2004) describes system failure in terms of the resonance of normal performance variability. This provides a convenient way of representing the non-linear propagation of events and also makes it possible to account for adverse outcomes in cases where there were no manifest malfunctions or failures. The principle of FRAM is to characterise individual system functions independently of how they may be connected in a specific situation. The characterisation of each function – or node – is done in terms of six aspects and the values of these aspects determine how nodes may be coupled under given conditions. To produce a description of functional variability and potential resonance, and to determine recommendations for damping unwanted variability, a FRAM analysis consists of four steps:

Step 1: Identify essential system functions, and characterise each function by six basic aspects or parameters. The six aspects are 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). Nodes and their aspects may be described in a table and can subsequently visualized in a hexagonal representation (cf. Figure 2 and 4 below).

Step 2: Characterize the context dependent variability of each node. For an accident analysis, the variability is known from the investigation data. In this case the analysis focuses on comparing the observed and the normal performance. For risk assessment, the variability may be derived from a characterisation of the common performance conditions (CPCs), of which there currently are eleven. These CPCs address the combined human, technological, and organizational aspects of each function. After identifying the CPCs, the variability must 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 characterisation of functions and their aspects. The aspects provides the basis for identifying how functions may be coupled. For example, the output of one function may be an input to another function, or produce a resource, fulfil a pre-condition, or enforce a control or time constraint. When the couplings between functions are found, this is combined with the characterization of performance variability from Step 2. In this way the analysis will show how the variability of one function may have an impact on others. This analysis thus determines how resonance, and ultimately adverse outcomes, can result from variability across functions in the system. For example, if the output of a function is unpredictably variable, another function that depends on this output as a resource may be performed unpredictably. Many such occurrences and propagations of variability may have an effect like resonance.

Step 4: Identify barriers for variability (damping factors) and specify required performance monitoring. Barriers are hindrances that may either prevent an unwanted event from taking place, or protect against the consequences (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). In addition to recommendations for barriers, FRAM can also be used to specify recommendations for the monitoring of performance and variability, as a way to detect and manage undesired variability. Performance indicators may thus be developed for every function and every link between functions.

2. Example of application to a complex incident

2.1 Summary of the incident

During a commercial flight to Paris-Orly, the Captain decided to perform an automatic landing due to the weather conditions at destination. Since the First Officer was not qualified for this procedure, the Captain took over most of the crew actions. On approach, he selected a wrong approach track on the HSI. Due to this error, the auto-pilot did not intercept the landing track (localizer), and the aircraft departed from the published trajectory. The Captain tried to recover from this situation by selecting, unsuccessfully, various modes on the auto-pilot. The aircraft crossed the glide path and twenty seconds later, the Captain corrected the selection of the track on the HSI. At the same time, he put the aircraft into descent, heading simultaneously towards the approach track. The auto-pilot was not able to capture the glide path, so that the aircraft continued its descent without external references. The Captain did not manage to stabilize his approach, and eventually initiated a go-around. The lowest height reached by the aircraft was 67 feet from the ground.

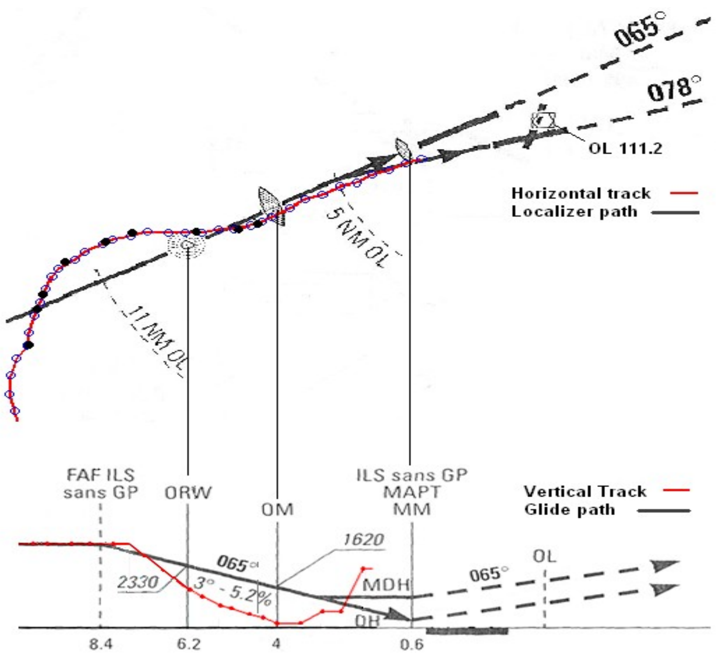

Figure 1: Horizontal (upper graph) and vertical (lower graph) tracks.

2.2 Description of the event using the FRAM Visualizer

The FRAM Visualizer is a tool which is used to describe the event as a set of functions and their associated control parameters. A node defines the basic information unit. There is no scale restriction to describe a function. In this example, it was decided to take the elementary action, such as the action of positioning the index on the HSI, to define the resolution of the scheme. This is in line with the pilot’s sequencing of actions: action – check – correction.

However, the availability of the data impeded the appropriate breaking down of the sequence and led to a more macroscopic approach for some functions.

We considered mainly the incident flight from the start of radar vectoring by Orly Approach to the go-around performed by the Captain. Nevertheless, some preliminary information was relevant to set the initial circumstances that developed throughout this phase of flight. Indeed, the first node corresponds to the "task-sharing decision".

The fact that the Captain departed significantly from the standard procedure, and improvised a sequence of actions, challenged the usual examination of a flight through the identification of deficiencies as compared to a standard flight. The standard flight could not be the sole reference to break down the actions performed into a comprehensive set of nodes. This justified the choice of taking into account a mix of:

- either standard procedures that were followed (high level of performance),
- or standard procedures that were not or poorly followed (low level of performance),
- or improvised actions that can be seen as an attempt to adapt to an unusual situation with more or less success.

Below is an example of a node corresponding to the action by the Captain of rotating the HSI index from the interception heading to the landing track. According to the operator's operating manual, this action is undertaken once the LOC CAP mode is displayed, and triggers a check by the First Officer.

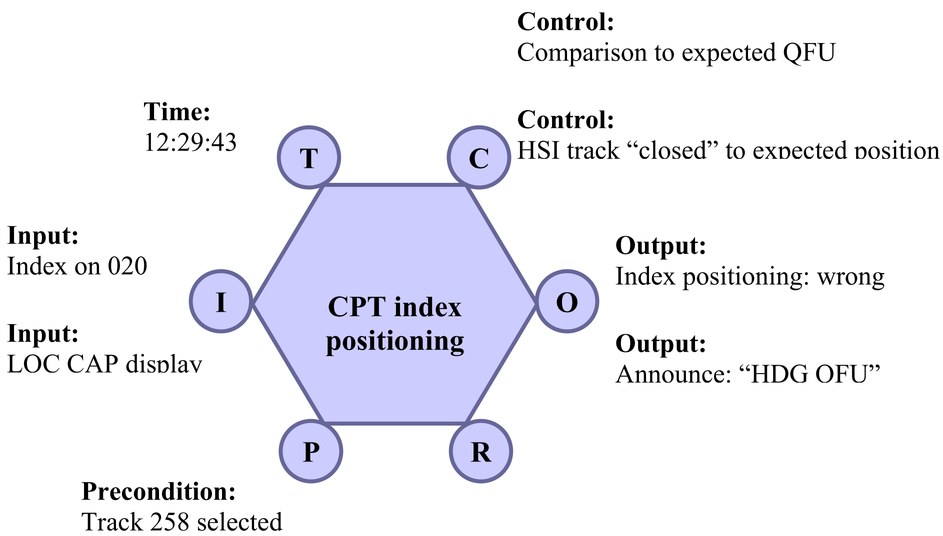

Figure 2: Description of a node by FRAM Visualizer.

Two inputs were identified: one triggered the action (LOC CAP display) and the other was a parameter that would evolve throughout the action. This choice will be discussed in Section 3.1.

The outputs include a callout that should have triggered a check by the first officer as well as the incorrect positioning of the index. In order to refer to the resonance approach, it was decided to take into account the variation of the output, between a "nominal" state and a "downgraded" state. In this latter case, the corresponding output was qualified as: "wrong", "failed", etc.

The selection of track 258 provided erroneous information to position the index. This information persisted during the action and was therefore considered as a precondition.

The control of the function can be seen as a test of the consistency of the respective positions of the index and the needle in accordance with the heading. The proximity of the tail of the needle with the intended landing track was misleading when the Captain positioned, as a reflex, the index on the tail of the needle. A quick check did not allow him to detect the discrepancy. However the reading of the heading led the Captain to feel that something was wrong. The figure below illustrates the display seen by the Captain, as compared to the one with the correct track selection.

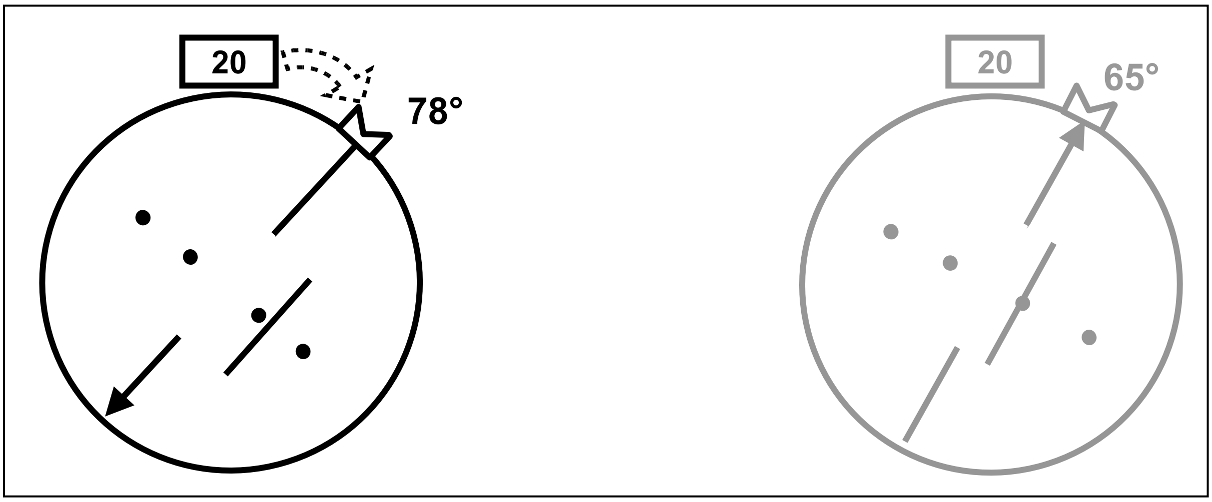

Figure 3: Left side: incorrect positioning of the index on the tail of the needle, taking into account the erroneous track selection (258°). Right side: intended position of the index on the head of the needle, with the correct track selection (065°)

At this stage, it should be noted that the functional approach helps to question the role and the description of every action, such as the one specified in the operating manual. For instance, while elaborating this node, in connection with the others, it was noticed that the operating manual did not specify what this check by the First Officer should refer to and more generally what was the intention of this action.

2.3 Connections of the nodes

The FRAM Visualizer automatically connects the control parameters of the nodes. This function provides graphic information regarding the influence that one parameter can have on several nodes.

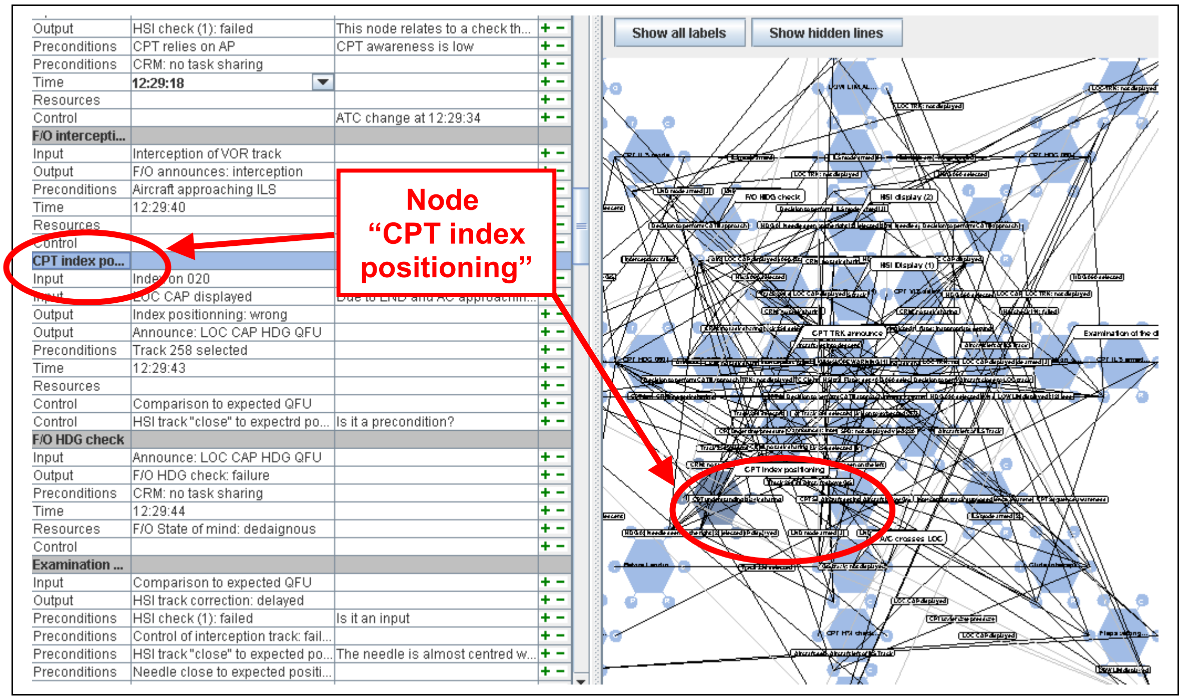

Figure 4: Automatically generated visualization by FRAM Visualizer

The automatically generated visualization produced a rather intricate scheme. It was then decided to rearrange the nodes in a time-sequenced scheme as shown in the next figure.

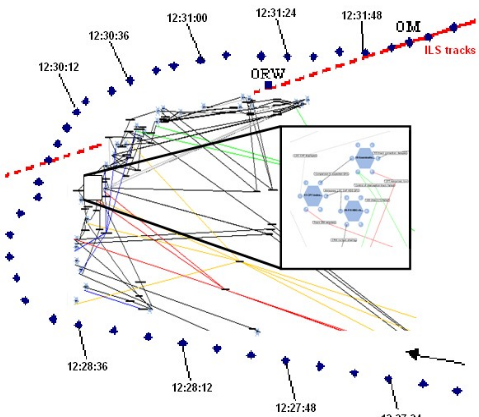

Figure 5: Horizontal track (blue dots) and FRAM nodes

For this representation, we decided to portray the Captain’s actions on the main track, and position the other nodes along side. The nodes are sorted according to whether they refer to:

- crew actions,
- system functioning,
- aircraft motion,
- system display.

This representation intrinsically defines some “components”, by analogy with dynamic systems.

2.4 Focus on three sequences of the incident highlighted by FRAM

It should be noted that it was not possible to collect any additional data or to undertake any simulation processes and, therefore, the statements that follow are only valuable for purposes of illustration but do not constitute, *stricto sensu*, new investigation findings. However, using the functional approach, the data was put together with a view to placing the actors back in their interactive context, in order to bring to light developed information. We provide hereafter three examples of sequences that refer to the Captain's perception and adaptation.

2.4.1 Captain's sequence awareness

The functional approach brought to light the fact that the Captain had a kind of sequence awareness, in the sense that his experienced partially counter-balanced his poor situational awareness. This is probably one of the factors that led him to alter the heading by forty degrees to capture the localizer track, after he crossed the approach track, whereas the situation displayed on his HSI would rather suggest that he keep the previous interception heading. Later on, the glide deviation triggered some reactions by the Captain. In particular, he called for gear extension as the aircraft was approaching the glide path. Even though this call came late in comparison the standard procedure, it shows that the Captain acted reactively. From this perspective, the fact that the aircraft crossed the glide path the first time probably increased the time pressure on the Captain. As he did not capture the localizer, he did not put the aircraft into descent at that time, nor did he call for the flaps. Instead, he focused his attention on his horizontal situation till he understood his mistake. When he noticed his wrong track selection, he tried to catch up with his vertical position. It would be interesting to deeper analyse the parameters that determine the Captain's sequence awareness. They certainly vary in importance according to the phase of the approach. In this respect, it's worth comparing the above-mentioned circumstances to the circumstances in which the Captain initiated the go-around.

2.4.2 Captain's understanding of the erroneous track selection

During the fifteen second sequence preceding the Captain's correction of the track selection, the aircraft was heading straight with wings level; there was no radio communication. The situation displayed on the HSI was "consistent" with an interception phase. The Captain armed the ILS mode and then expected the autopilot to capture the localizer. He was then, for the first time, in appropriate conditions to scrutinize his HSI and discover the discrepancy.

2.4.3 Captain's decision to go around

As the aircraft crossed the glide path for the second time, the "glide slope" warning sounded, followed by an announcement by the First Officer. The Captain disconnected the auto-pilot, turned left to intercept the landing track as the needle became alive on his HSI. He then re-connected the auto-pilot and, within a few seconds, disengaged it and initiated the go-around. According to his testimony, the Captain was not aware of his vertical position and decided to go-around because he did not feel stabilized. The use of FRAM suggests that this feeling may be influenced by the gap between the modes displayed on the FMA and the ones expected at this stage according to the operating manual. Indeed, none of the three modes expected were displayed on the FMA.

3. A contribution to further developments to FRAM

3.1 States, functions and definitions

The FRAM Visualizer was initially designed to describe functions, such as actions by the crew. However, it can be seen that, for instance, the node shown as an example in section 2 is a mix of an action, the Captain positioning the index, and a change of state, the rotation of the index. In this case, the understanding of the consequences of this function was not hampered. The situation becomes more challenging regarding the evolution of the HSI display in accordance to the aircraft position. Therefore, it appeared necessary to distinguish the functions that refer to a crew action from the functions referring to change of states of systems such as the HSI or the autopilot mode announcement (FMA). From this perspective, it became necessary to define the control parameters of a node in accordance with its nature.

From an "action" perspective, an input is something which triggers an action that produces an output. The control parameter is understood as an immediate check, associated with an action. A resource-consuming control action, such as a check prescribed in a standard operating procedure, is described via a dedicated node. The precondition is understood as a contextual element that influenced the result of the function, that pre-existed to the function and that varied slowly during the function's processing. The fact that the crew experienced poor CRM was a precondition of most of the functions during the approach.

From the "state" perspective, an input is something processed by the system to produce the output. The precondition is then a necessary condition for the state to evolve. For instance, the fact that the localizer track be captured was a precondition for the capture of the glide by the autopilot. The periodic check by the automatic system of the situation - the non interception of the localizer track – did not allow for the successful change of state of the autopilot, from an armed mode to a track mode. From this perspective, the resource refers to the kind of energy required.

Time is a parameter which requires further work to be taken into account. During this study, the associated tag was simply used to position a node in the sequence. Time should intervene as a control parameter of the variation of the function.

3.2 Multilayer analysis

The need to take into account the interactions between different components such as systems or crew members calls for a rearrangement of these components in various layers. From this perspective, each layer would describe the evolution in time (chain of functions or changes of states) of homogeneous components. It would be then necessary to represent the interactions between the layers. This kind of distinction would facilitate comprehension of the interactions, as well as the identification of the resonance phenomenon. Indeed, components of the same nature tend to evolve on a similar time scale. For instance, the aircraft followed a quite simple track during the approach, marked by three changes of heading; at the same time, the FMA displayed a multitude of different modes.

4. Conclusion

The functional approach should lead us to question every action performed or missed. In this sense, the development of this method should help with the collection of data in the course of an investigation. Moreover, it highlights the deficiencies of a function itself, as well as those related to the immediate context of an action. The connection of the nodes through their control parameters shows the evolution of this context.

However, the analysis must further consider systemic deficiencies. How did an adverse outcome propagate? How were its effects dampened or heightened? To answer these questions in relation to a complex environment, it appears necessary to pursue the development of the analytical tools, and to better describe the evolution over time of the interactions. The challenge is to point out some necessary factors that condition the stability of the standard “flight structure”.

References

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