A METHOD FOR OPTIMIZING AIRCRAFT MAINTENANCE PLAN

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Abstract. *This paper presents a method for optimizing an aircraft maintenance plan using aeronautical systems parameters. The method includes the assessment of the system structure, its subdivision in components and the relation between each component and its particular function. Once having this information, the following steps are prescribed by the proposed method: make a Failure Mode and Effect analysis in order to identify critical failures, its probability of occurrence and the correlation between failures and some parameters available in the system. Then, an experiment must be defined and carried out in order to describe how the variation of the chosen parameter affects the system and how the monitoring of its value can optimize the aircraft maintenance plan. The paper presents a theoretical example, considering a typical elevator system mechanically controlled.*

Keywords*: Condition based maintenance, Maintenance plan, Aeronautical system*

1. INTRODUCTION

Nowadays, to reduce the maintenance costs of aircraft is a necessity to airlines due several factors. Fuel prices are higher than they have ever been, the aircraft design cost is increasing due to more strict regulations and this cost is transferred to the price the operators pay for the aircraft, recent terrorist attacks are making people prefer to travel by other means of transports .Since the mentioned factors can not be controlled by the operators, their focuses are on the maintenance plan and operational procedures.

An increasing number of research projects in this area reflect the worries brought about by the scenario just described. This paper proposes a simple method that can be quickly implemented by the airlines to yield the needed results as far as maintenance plan and operational procedures are concerned. This method is more closely related to condition based maintenance, which is defined by three steps: data acquisition, to obtain relevant data to system health; signal processing, to handle the signals or data collected in step 1 for better understanding and interpretation of the data; and finally, the maintenance decision making, to recommend maintenance efficient policies (WILLIANS *et al*, 1994).

2. PROPOSED METHOD DESCRIPTION

The proposed method can be described schematically as shown in Fig. 1.

The first step is to assess the system structure, its subdivision in components and the relation between each component and its particular function. The following steps are to identify the engineering parameters related to each sub-function and system component and make a Failure Mode and Effect analysis in order to identify critical failures, its probability of occurrence and the correlation between failures and some parameters available in the system. The choice of the adequate parameters is made and an experiment defined and carried out in order to describe how the variation of the chosen parameter affects the system and how the monitoring of its value can affect the aircraft maintenance.

3. THE AIRCRAFT ELEVATOR SYSTEM

The method proposed herein is detailed through a theoretical example, that of an aircraft elevator system, with classical characteristics of a conventional mechanical control system. This is described below.

The pilot controls the elevator system through a column inside the cockpit and the movement is transmitted through a four bars mechanism to the forward torque tube. There is a steel cable that connects the forward torque tube and the rearward torque tube. Between this torque tube and the control surface, there is another four bar mechanism.

Due to safety reasons, each aircraft has two identical systems connected, so if one of them becomes inoperative, it is possible to continue a safe flight until the nearest landing field using the other one. Figure 2 shows a schematic model of the described elevator system.

Usually, the control cables path has some direction changes which are corrected through pulleys. However, this model does not consider the pulleys due to its minor effect in force transmission. Likewise, the simplified model does not consider the grommets and fairleads that prevent one cable to touch other aircraft parts and avoid wear and jamming.

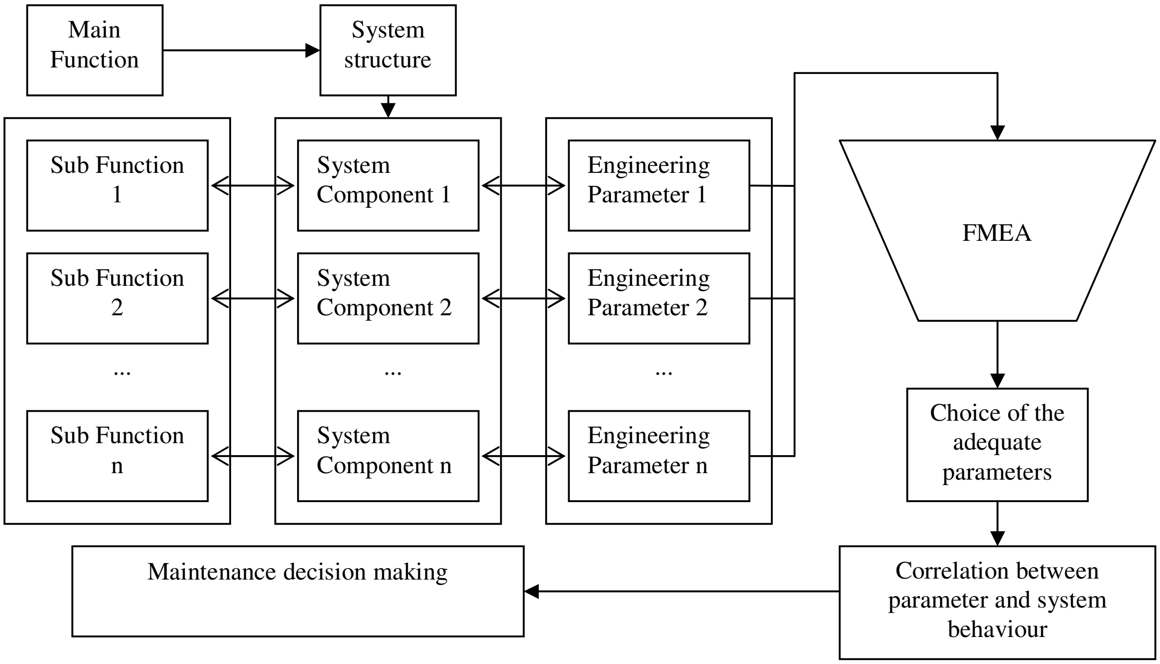

Figure 1 – Method schematic description

It can be noticed in Figure 2 the presence of hydraulic power actuators and tension regulators. Power actuators allow the pilot to control the aircraft even if the aerodynamic loads are excessive high and the tension regulators preclude the necessity of defining a high adjustment tension since it can compensate the effect of thermal expansion differences between the aircraft structure and the control cables. Tension regulators, though, are not mandatory and not used in lots of aircraft models due to the increase of weight and complexity (it is another failure source, when added to the system). In the case study presented herein there are no tension regulators in the elevator system due to design choice.

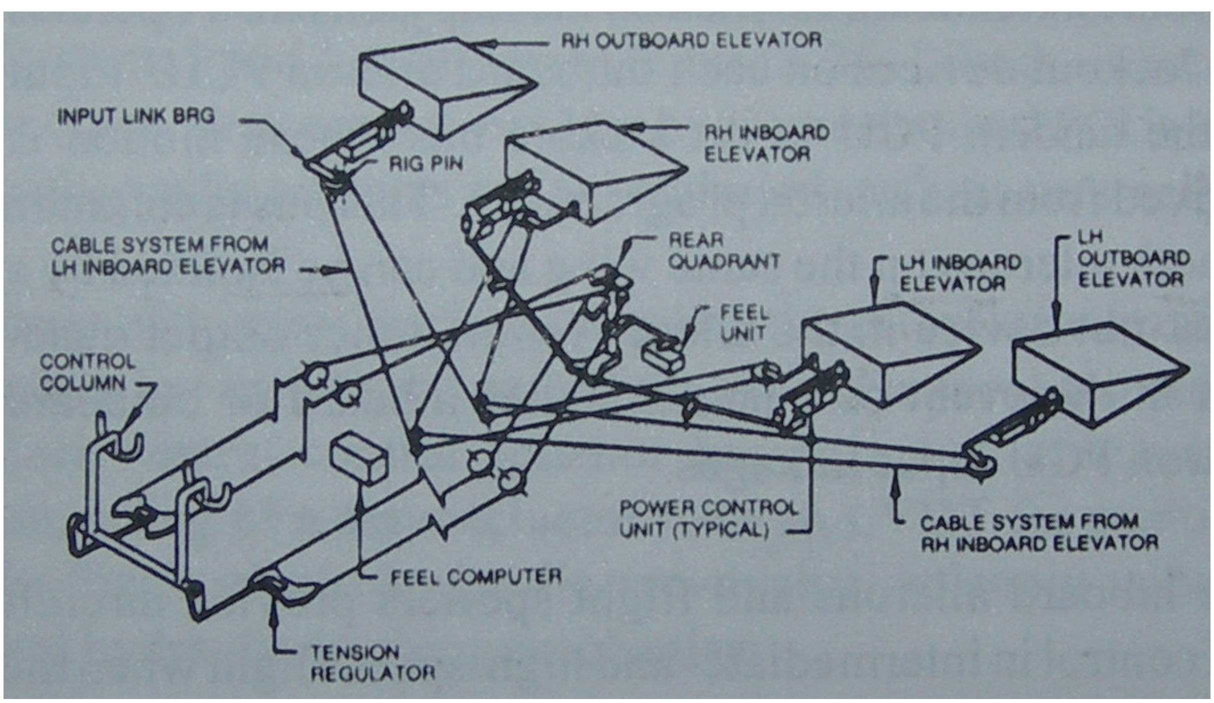

Figure 2 – Elevator control system (source: RAYMOND and CHENOWETH, 1993)

4. THE SYSTEM FUNCTION ANALYSIS AND STRUCTURE

The first step to analyze a system is to divide it into parts and determine its functions. In the elevator system, for example, it can be stated that its main function is to provide the pilot a mean to longitudinally control the aircraft.

The following step is to determine the sub-functions of the system, such as:

- ✓ transform the column movement into a bellcranck movement,
- ✓ transform a circular movement in a linear movement,
- ✓ transform a bellcranck movement into a surface movement.

For each sub-function, it is possible to determine the component of the system that performs it. This corresponds to the system structure. Figure 3 shows the functional analysis and Tab. 1 shows the system structure of the elevator system.

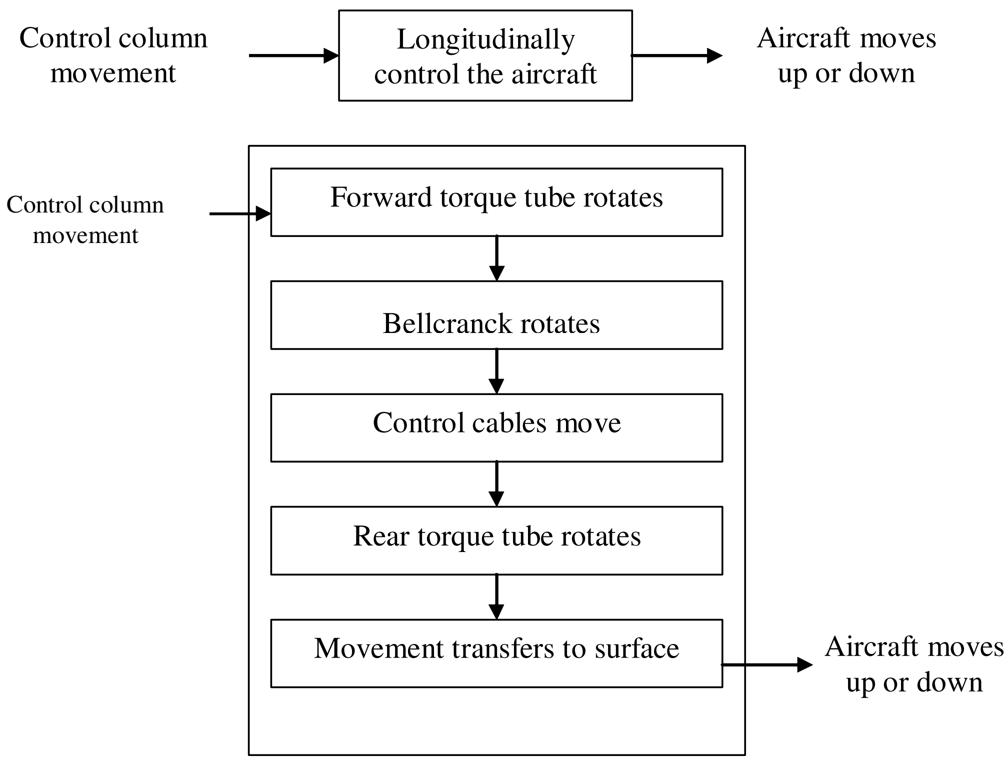

Figure 3 – Function Analysis of the elevator system

5. THE FAILURE ANALYSIS

Failure Mode and Effect Analysis (FMEA) is a design tool that can prevent problems and identify the best solutions for each one of them (PALADY, 1997). Considering this definition, it is easy to realize that FMEA can also be used as a failure prognostic tool, since the consequences of each failure are already mapped. The FMEA tool can be used as a mean to select a component to be monitored using the following criteria: importance of the lost function and the identification of an engineering parameter that can be monitored to detect the component / system degradation.

A simplified FMEA of elevator system is shown in Tab. 2.

Table 1 – System structure of the elevator system

Components	Functions
Control Column	Receive the input from the pilot
	Transfer the pilot command to the four-bar mechanism
Four-bar mechanism	Transform the control column circular movement in a linear rod movement
Forward Torque tube	Transform the four-bar rod linear movement into a circular movement
	Connect right and left elevator systems in order to make both surfaces move together
	Fix the bellcrank
Cables	Transfer the bellcrank movement to the rear torque tube movement
Rear Torque tube	Transforms the cable linear movement in a circular movement
Four-bar mechanism	Transmits the rear torque tube movement to the elevator surface
Elevator surface	Move in order to make the aircraft goes up or down, depending on the pilot's input

According to FMEA analysis, a candidate to be monitored would be the tensions on the cables. The reasons for this choice are the following:

- ✓ The rupture and jamming events would be evident to the pilot and there is no parameter available to check its degradation. Usually, in aircraft maintenance plans, there are general and detailed visual inspections, whose objective is to detect defects on the parts that can progress up mechanical interferences, jamming or even rupture.
- ✓ The dead spot failure mode can be eliminated because its associated parameter is the system vibration, but since the aircraft is operated in a lot of different weather conditions it would be too difficult to establish a correlation between system vibrations and wear on the system component attachments. Besides, there is also in the maintenance plan a backlash check for the system that would expose this kind of problem.
- ✓ There is no easy way to check cables wear. It is necessary to access the cables and inspect the whole cable, inch–by-inch, looking for wear and broken wires. It is pretty hard to perform this inspection since usually there is not enough light or space. Although it is not difficult to identify a broken wire touching the cable, it would be almost impossible to identify a 40% wear in a single wire of the cable, as recommended by the AC 43.13-1B regulation (FAA Advisory Circular).
- ✓ The pulley degradation has been not considered in this study due to the lack of measuring parameters available to evaluate its effect on cable tension and due to the fact that its effect is considered negligible when compared to the cables wear, since the pulley design and installation are adequate and approved according to aeronautical requirements. Furthermore, the probability of a pulley degradation is smaller than that of the cable.

6. THE EXPERIMENT DEFINITION

In an elevator system as described above, the value for tension adjustment must be determined very carefully since if the tension is low, than the return cable might present sag which can cause friction between the cable and other aircraft parts. On the other hand, if the tension is too high, then the system friction is also too high, what requires a greater effort from the pilot to control the aircraft.

The adjustment tension is determined for a defined temperature. Then, an adjustment curve is built that relates the cable tension values for each temperature. This is necessary because the cable and fuselage materials are different and have, consequently, different thermal expansion coefficients that cause variation of tension when the temperature varies.

Table 2 – Simplified FMEA of the elevator system

Components	Failure Mode	Failure effects	Failure causes	Severity	Occurrence	Parameter
Control Column	Rupture	surface can not be commanded		In all these cases, the aircraft still can be controlled using the pitch trim system (which is common in comercial airplanes). Pilot's work load increases substantially and manoeuvrability decreases. In jamming cases, other system characteristic that can be useful to minimize hazard is the possibility to disconnect left and right systems, so if only one is jammed, the other one keeps operational	Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration
Four-bar mechanism	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration
Forward Torque tube	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration
Cables	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	Cable wear diminishes cable tension		Improbable	Cables tension
Rear Torque tube	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration
Four-bar mechanism	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration
Elevator surface	Rupture	surface can not be commanded			Extremely improbable	
	Jamming	loss of actuation			Extremely improbable	
	Dead spot	delay between command and surface movement	wear on the attachments		improbable	Vibration

The cable tension is expressed by a following equation: (LOOS&Co, 2007):

$$W = E.\frac{D^2}{G} \qquad (1)$$

where:

- W is the cable tension [N];
- E is the cable elastic stretch (% of length);
- D is the cable diameter [m] = 0.003175 [m] for the example;
- G is a factor that depends of the cable material and type of construction. In this case study, the cable material is stainless steel cable, diameter, 7x19 construction (which means 7 strands of 19 wires each). Thus, the value for G is $2.34x10^{-9}[m^2 / N]$ for the example

Using the data provided above, it is possible to estimate the diameter of a single wire as being:

$$d_{wire} = 2.39x10^{-5} m \quad (2)$$

If a single wire has its diameter diminished in 40% (according to the AC 43.13-1B regulation), the cable diameter would decrease by $0.4x2.39x10^{-5} m = 9.54x10^{-6} m$.

For this figures, Eq. (1) yields:

$$W^{'} = \frac{E}{G} D^{'2} = \frac{E}{G}\left(3.18x10^{-3} - 9.54x10^{-6}\right) = \frac{E}{G}\left(3.16x10^{-3}\right) \quad (3)$$

The comparison between Eq. (1) and Eq. (3) results:

$$W^{'} = 0.99xW \quad (4)$$

The information expressed by Eq. (4) can be posed as: if there is a wear out of the specified limits, the cable tension is expected to decrease at least 1%.

Considering this information, what shall be done is the measurement of the control cables tension and comparison between the value found and the adjustment value. If there is a decrease greater than 1%, it is recommended to perform an inspection looking for cable wear. Otherwise, there is no maintenance needed.

The interval between two tension checks would be the same determined for the cables inspections.

7. FINAL COMMENTS

The proposed method is very important to determine systems, components and parameters that can be used in a condition based maintenance program.

In order to have a successful program it is essential to have means to measure the relevant parameters in an adequate frequency to prevent unexpected failures from happening.

In the example presented, it would be very important to have accurate measurement equipment, since the variation of the analyzed parameter is very small. This fact would make the cable tension a bad parameter if the method was used in a system that includes a cable tension regulator, because this component would compensate not only the temperature stretch variations, but also the cable wear effect. However, the method would be yet a good option to be used since an adequate parameter is found.

Likewise, the pulleys degradation effect on the system was not considered since it would be too small to be reasonably measured. To cover the pulley degradation possibility, the aircraft maintenance plan includes a periodic visual inspection of these parts to preclude problems.

As an extension to further applications, the proposed method could be also used in the product design phase, since it would be much easier to include sensors or to provide access to measurement points during the product design phase. Within the Integrated Product Development (IPD) environment, this approach would be named “design for condition based maintenance”

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