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Short communication

Engine to wing structural design under critical loads caused by a propeller blade loss

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ABSTRACT

To support the propeller blade loss loads in a turboprop aircraft the engine mounting system has to be carefully designed. The joints have to withstand the flight loads, however, during the blade loss event they have to fail before the wing gets damaged. Using a FEM model and Monte Carlo simulation techniques the possible failure sequences for a broad spectrum of flight conditions have been obtained, including different propeller frequencies, blade loss sizes, angular positions where the blade is lost and also material properties. The structural model includes non-linear behavior, damages, and several types of failure together with stochastic variables which can incorporate parameter uncertainties. Finally, the pylon to wing support is designed to guarantee, with high level of confidence, no major hazard on the aircraft due to this dynamical phenomenon.

1. Introduction

Although structure performances have been greatly improved in the last years, the huge increase in the demand of air traffic is responsible for the fact that the rate of occurrence per airplane departure for propulsion system malfunction, or inappropriate crew response accidents, has remained essentially constant for many years, as it is mentioned in [1]. In aviation safety databases like [2–6] or [7] are reported more than 644 engine occurrences since 1919 until July 2017 (powerloss, fire, flame-out, fuel issues, propeller reverse pitch, simulated engine failure, etc.). Specifically, they include the following occurrences: 64 uncontained engine failures, other 54 engine separations and at least 35 turboprop blade separations. One of the last accidents was on the 1st of November of 2014 where a de Havilland DH-114 Heron aircraft made an emergency landing following the in-flight separation of a turboprop and the prop struck onto other engine causing substantial damage as it is documented in [7]. Some months later, the 16th of April of 2015, a Swearingen SA227-AC Metro III was substantially damaged after an uncontained engine failure during the climb. A post-accident examination of the airplane (documented in [6]) revealed that a rotor from the right engine had separated.

1.1. Turboprop blade loss phenomenon

Blade loss is a relatively common flight incident in turboprop airplanes. As an example, the 25th of October of 2013 where a Fokker F-27 Friendship 500F was damaged, Rolls-Royce Dart 532-7 engine suffered an uncontained failure. This resulted in the loss of the propeller and the front part of the engine. Propeller blades sliced through the fuselage of the airplane, exiting on the other side as it is documented in [6]. On one hand, accidents in turboprops are less common due to the fact that the engines have fewer moving parts than in turbofans. They offer greater reliability, smoother operation and have longer time between overhauls. On the other hand, more hours before they have to stop for inspection implies to increase the probability of a blade loss due to unnoticed crack growth. This type of cracks is deeply studied in [8] which joined to the obvious safety implications. It confirms the importance of thoroughly studying the blade loss event with all the parameters of influence. The blade loss event probability is related to diverse factors such as: blade material, blade structural design, time between overhauls, NDE techniques used…This parameter, of significant importance, can be obtained by the manufacturer/operator of the aircraft.

Pylon to wing support for aircraft engines is designed to withstand the loads produced during the normal flight operation without transmitting excessive vibrations to the wing that could compromise the structure. In normal conditions the largest loads occur in the thrust and vertical directions. Nevertheless, some events of engine malfunction may produce an imbalance and compromise the aircraft structure. In most cases, the powerplant installation design makes that no single failure or malfunction jeopardizes the safe operation of the airplane. Each powerplant is isolated from the others and configured in order to stop the rotation of any engine individually if necessary. An inoperative

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engine does not constitute a safety issue since airplanes are designed to fly under such circumstance. However, once the blade is lost a powerful vibration is produced in the engine as it is reported in [9] and shown in Fig. 8, but the consequences vary function of several parameters, being the blade loss size one of major importance [10,11]. In order to bound the dynamic loads transmitted from engine to the pylon and, finally, to the wing the stiffness and strength of the elastomeric joints must be thoroughly selected. They are designed so they fail to interrupt the load path to the wing and, thus, avoiding the failure of any other part of the airplane.

In order to study the phenomenon two important techniques must be selected: an appropriate parametric analysis tool together with a model order reduction technique. Among the wide variety and quantity of these techniques, the Monte Carlo Technique (MCT) and the Craig-Bampton reduction have been chosen regarding their compatibility, versatile characteristics and simplicity [12–15].

This paper is structured as follows. After a brief description of the structural model, the selection of the Monte Carlo Technique, the parameters of influence (with their distribution functions) and the load cases are presented. Afterwards, the results are analyzed and the key parameters are identified. Finally, it is shown the procedure to obtain with any desired confidence level the pylon to wing allowables. Along these sections some clarifying examples are given.

2. Description of the model

The most severe failures occur when it is impossible to prevent severe vibration transmission to the structure of the airplane. Most common ones are propeller unbalance at assembly or a crack in the propeller hub that can possibly result in propeller blade loss, to which this paper is devoted. The engine mounting system (EMS) model must absorb these vibrations and, if necessary, detach the engine from the structure before fatal structural damages may occur. In order to simulate the dynamic behavior of the phenomena, two differentiated elements of the structure have been modeled: the engine and the engine mounting system (also referred in the article as pylon). The hypothesis of a rigid and fixed wing is used in the model for the boundary conditions and limited mass and stiffness matrices are used, with special attention to the joints.

The representative case that has been chosen is a heavy-duty military transport turboprop. A draft of the structure is shown in Fig. 1 and more detailed descriptions of the models can be found in [11,16], where different hypotheses for the simulation are considered and compared in detail.

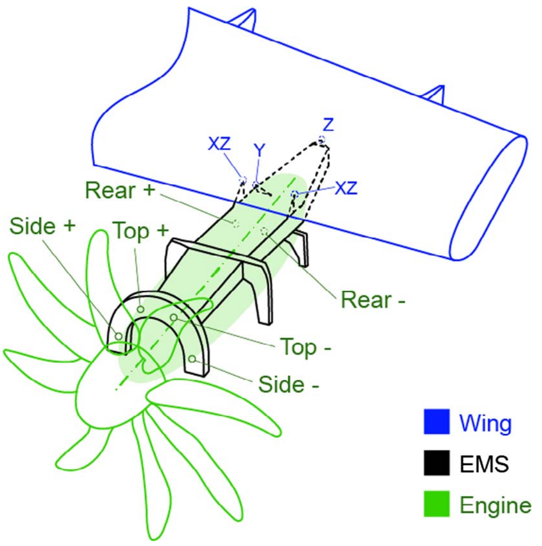

Fig. 1. EMS schematic sketch: EMS to engine and EMS to wing joints.

2.1. *Engine*

The selected model for the engine has two important characteristics: it is reliable (it has been verified and checked, see [11,16]) and with a reduced number of degrees of freedom.

A highly dynamic phenomenon requires a model with mass, inertia and eigenmodes that matches the real structure. It is also necessary the non-linear behavior of the six elastomeric devices, which has been adequately modeled: linear stiffness in shear and non-linear in compression/tension, and different failure criteria depending on the axis. A draft of their location and position on the structure is shown in Fig. 1.

On the other hand, the Monte Carlo technique that has been used for the analyzes requires low order models, otherwise it would have a prohibitive computational demand. The Craig-Bampton reduction has been chosen in order to fulfill this requirement [12].

2.2. *Engine Mounting System (EMS)*

This structural element connects the engine to the wing and, therefore, supports and transmits the forces that reach the wing. Additionally, when this structural element is not considered in the blade loss simulation the failure results are different, as shown in [11].

The engine joint is designed through the elastomeric devices, while the attachment to the wing (also referred as pylon to wing support) consists of four points: two connected to the forward part of the wing in X and Z directions, and other two to the rear part of the wing, of which one support loads in Y and the other in Z (see Fig. 1). Therefore, this attachment can be designed through the comparison of these loads with the corresponding allowables. Fig. 2 shows the volume (inside red box) in which no allowable (F_{x1} and F_{z1},F_{x2} and F_{z2},F_{y3} and F_{z4}) has been reached, and, therefore, there is no structural failure. It also shows an example of the forces (blue line) and the required allowables (green box) to support the load case.

2.3. *FEM analysis considerations*

Different schemes are considered for the integration of the dynamics of the problem (Eq. (1)). In every case, the time step is a key parameter which is obtained in relation with the highest eigenmode required and

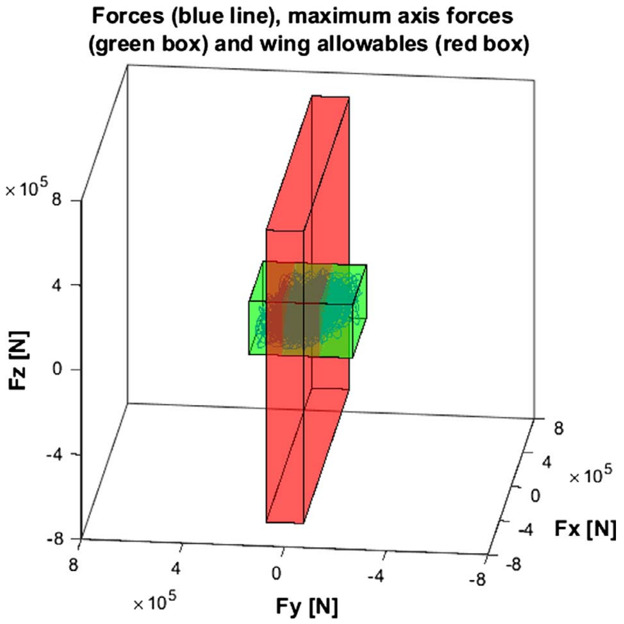

Fig. 2. Pylon to wing force evolution (blue line), its maximum values (green box) and the allowable limits (red box). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)