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# Study of electric arc ignition, behavior and extinction in aeronautical environment, in presence of FOD

Guillaume Belijar, Gaetan Chanaud, Loïc Hermette and Aurore Risacher

**Abstract**—Current development of more electrical aircraft and future all electrical aircraft leads increased power densities and power on board. The increase in power densities take the form of increased voltage (230/400 V<sub>ac</sub>, ± 270 V<sub>dc</sub>) and/or decreased distances between conductors. The addition of these evolutions leads to higher probability of electric arc, which might be potentially more destructive. In this paper electric arcs ignited by a Foreign Object Debris (FOD) that shorts out two busbars, are characterized. The electrical parameters meet the aeronautical standards, i.e. 230/400 V<sub>ac</sub> at 400 Hz. A statistical study of the impact of the FOD geometry on the arc size is carried out with the aim to give guidelines for the development of passive protections. The results show that there is no direct correlation between the arc dimensions and the FOD diameter or mass, although the object behavior was different. In a second part the electric arc was characterized in terms of dimensions over time and electrical signature to state on the time in which active protection should trip and to try to find a signature of the arc to detect. The results tend to prove that the dV/dt might be a relevant marker of the arc.

**Index Terms**— FOD, electric arc, aircrafts, busbars

## I. INTRODUCTION

The evolution toward more electrical aircrafts has major impact on today and tomorrow aircrafts architecture [1]. Besides the replacement of parts of pneumatic and hydraulic energy vectors by the electrical one and the increase in electrical power available, this evolution is characterized by an increase of the voltages levels (230/400 V<sub>ac</sub> and ± 270 V<sub>dc</sub>) and a densification of the systems with the aim of increasing power densities. While the goals and benefits of this strategy are well identified (lower the mass of the aircraft and the fuel burned), it comes with many challenges to tackle. One of these, directly related to the changes in the voltage amplitude and the reduction of the distances between conductors at different potentials, is the increased risk of electric arc ignition, potentially destructive (flight SR 111, R-100/61-ZR, A319 in 2009). In parallel to these changes, another impacting factor is the move toward variable frequency generators ranging from 360 to 800 Hz, whereas high frequency increase the risk of long arc duration. One major concern in the study of electric arc in aeronautical environment is the presence of FOD. Indeed, a metallic object is able to initiate an electric arc if it shorts out two conductors. This kind of event is very hard to quantify and rationalize as many factors can impact the

phenomenon occurrence and behavior, such as the object and conductors geometry, nature, the object dynamics (dropped or static), the potential presence of other pieces in the vicinity of the arc and the electrical parameters (voltage, current and power magnitude and limits, signal frequency). With the addition of the electric arc chaotic behavior, its global study is very complex. The most important factors in aeronautical systems for the arc events and their impact are summarized in Fig. 1.

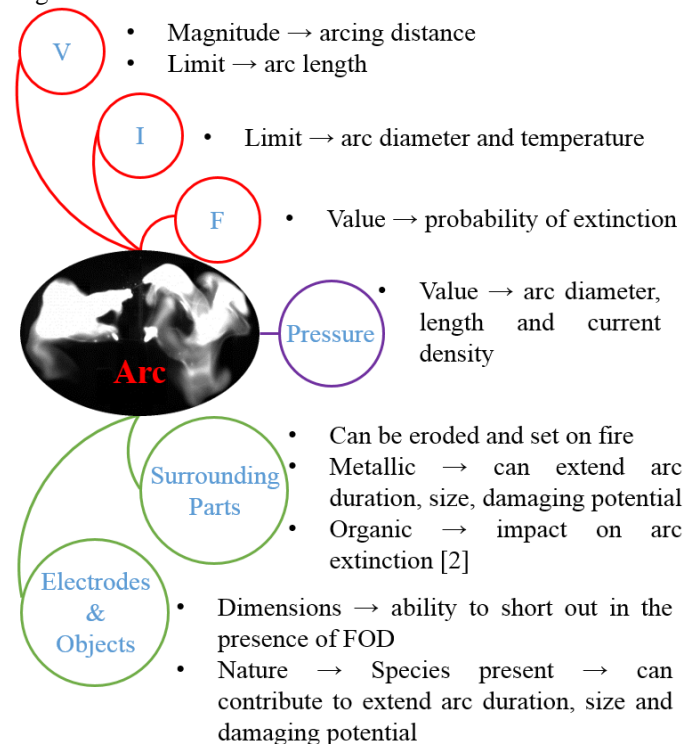


Fig. 1. Predominant factor impacting the arc ignition, behavior and extinction in aeronautical environment.

From the industrial angle, two strategies are being developed, passive:

- Segregation distances between bars
- Insulating material
- Mechanical protection to prevent FOD from entering in contact with electrodes

and active:

- Arc detection devices (Arc Fault Circuit Breaker and Solid State Power Controller)

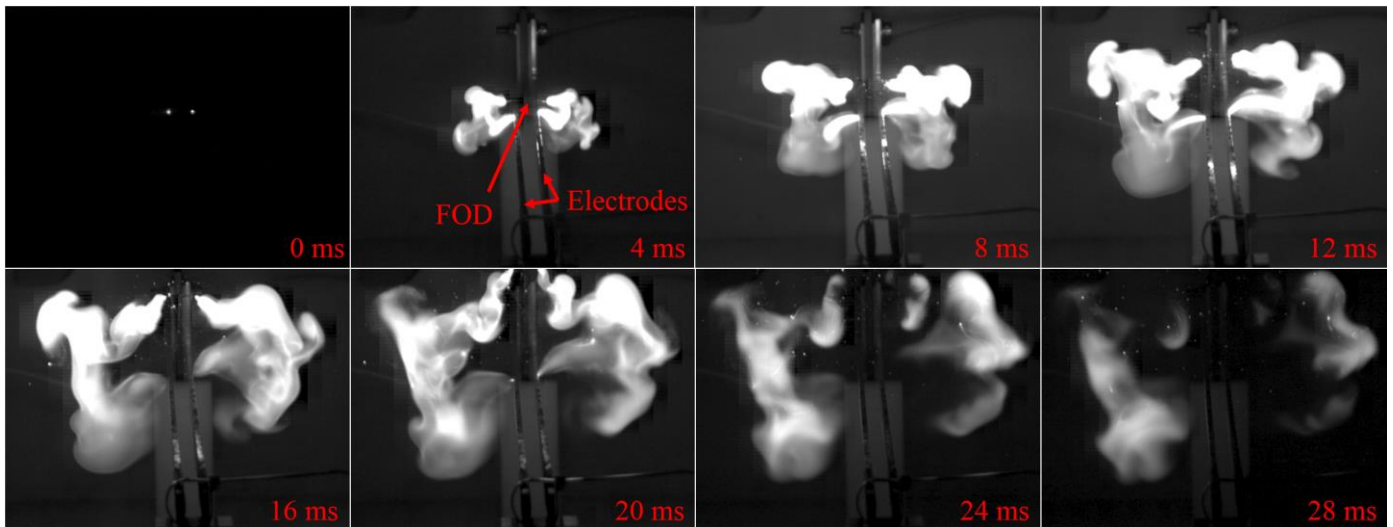


Fig. 2. High speed capture of electric arc initiated by an aluminum solid wire with 0.7 mm diameter. The arc is extinguished after 21 ms (zero current and no cathodic and anodic spots visible), so the last two pictures are residual luminescent plasma.

Obviously, it is impossible to conclude in one study on how an arc will behave under all the possible combination of parameters presented above. In the present article, two parameters are studied, the object nature and geometry, all the others being fixed. First a statistical analysis is realized to determine whether a relationship exists between the object type and the object and arc behavior. The industrial purpose of this section is to give, if possible, guidelines for the design of mechanical protections. In a second time, the electric measurement are correlated to high speed camera images of the arc to correlate the events to electrical signatures. The aim of the second section is to provide reference signature for the electrical signals in the presence of an arc.

## II. EXPERIMENTAL SETUP

The experimental setup used to simulate a part of aircraft power distribution system is presented in Fig. 3. The left and right electrodes are connected between two phases of a three-phase Pacific power source 65 kVA. The phase to phase voltage is set at 400 V<sub>RMS</sub> and the frequency at 400 Hz, in agreement with recent aircraft standards. It is important to note that this is not the most critical configuration from the electric arc point of view, the frequency being allowed to vary between 360 and 800 Hz. This variable frequency brings many challenges such as a diminution of the arc extinction probability at high frequency. The arc voltage and current are measured thanks to HZ-115 and Hioki 3275 probes respectively, connected to an oscilloscope Hioki MR8847-02. The video acquisition is achieved thanks to a Photron SA4 high speed camera. The framerate is set at 20 000 fps with a 1/30 000 s shutter, approximately 2.5 s can be recorded, enough to observe the entire arc duration (the arc is extinguished manually if it last too long, in aircraft condition it is very unlikely to observe an arc this long as circuit breaker would have tripped before). To avoid overexposing the camera sensor in the presence of the arc, 64 or 400 filters are used. All the acquisition devices are triggered on the contactor 2. Temperature and humidity are measured but not controlled.

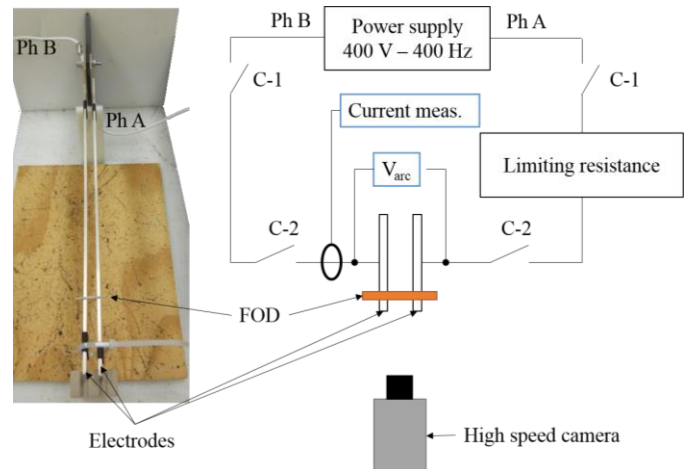


Fig. 3. Scheme of the experimental setup. Geometrical details are not given due to confidentiality matters.

The choice of the objects used as FOD is rather complex. The question being: how to simulate a FOD when it can be almost anything (screw, wire, metal shavings, etc.)? As it is impossible to test every objects, conductive wire were selected as FOD. These objects present simple geometry that can be easily controlled and varied (in length, diameter and nature of the metal), allowing to study the impact of the object shape and nature. In the present study two kinds of wires were tested, cores of aeronautical cables (stranded, gauge from 20 to 08 AWG) and solid cables (diameter from 0.3 to 4 mm). Four different metal natures were selected, copper, Ni-plated copper, aluminum and stainless steel. The details of the FOD tested are summarized in the Table I.

TABLE I  
Summary of the FOD tested

Type	Metal nature	Diameter (mm) / Gauge	
Stranded	Aluminum	0,7 / 22	
Stranded	Ni-platted copper	1 / 20	1,7 / 14
		1,2 / 18	2,7 / 10
		1,4 / 16	3,7 / 08
Solid	Aluminum	0,3	1,6
		0,4	1,8
		0,7	2
		1	3
		1,5	4
Solid	Stainless steel	0,7	2
		1,5	
Solid	Copper	0,7	2
		1,5	

### III. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Statistical study of arc ignition

The first step of the study was a statistical study of the arc ignition for the different FOD used as defined in Table 1. Prior to the detailed description, a major observation was that in every case an electric arc occurred. This is very important because it means that, in this specific setup with the electrical parameters used, when a foreign object is present and static on the electrodes, it will always lead to an electric arc. However, all the arc observed were not equivalent in terms of duration, extinction and volume occupied by the plasma.

In order to attempt to understand the origin of these different behavior, an analysis of the FOD behavior is presented in the Fig. 4. Two cases are discriminated, when the FOD is ejected, when the FOD is welded on the electrode (either on one or two sides).

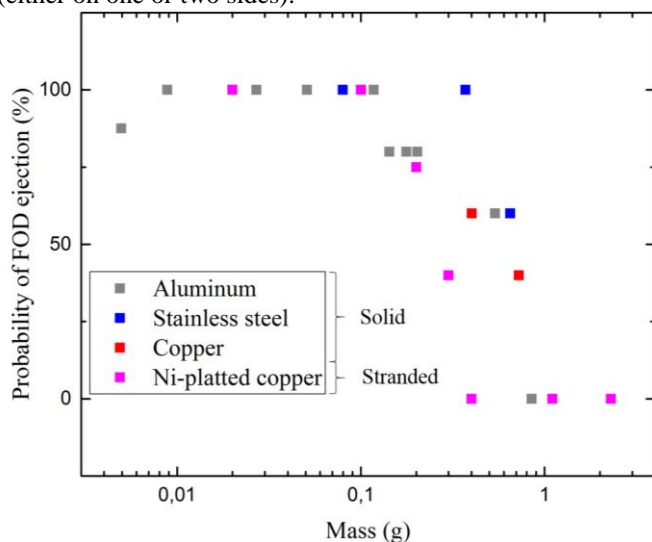


Fig. 4. Probability of FOD ejection as a function of their mass.

The first observation from the figure above is that the FOD behavior is correlated to the object mass. This is likely due to the fact that the force opposed to the ejection is directly

proportional to the object mass, making heavier objects harder to eject. The second observation is that stranded and solid wires present the same comportment. This means that the interface between the object and the electrodes have little impact on the arc behavior. As it shows no difference, to keep simpler explanations, for the rest of the study the analysis will be focused on solid wires. The third observation is that there is a distinct transition between FOD being ejected and welded when the mass increased. Following this observation, the initial hypothesis was that, when the FOD is ejected, it allowed the arc to expand more easily as the arcs would stay “attached” to the object (as in Fig. 2). If this assumption was verified, it would give a useful tool to sort the FOD as a function of the damaging potential of the arc they can initiate, the lighter objects leading to more damages. In order to assess this, the arc dimensions were computed thanks to the high speed camera acquisition. The raw and processed images for three different cases with increasing size can be observed in Fig. 6.

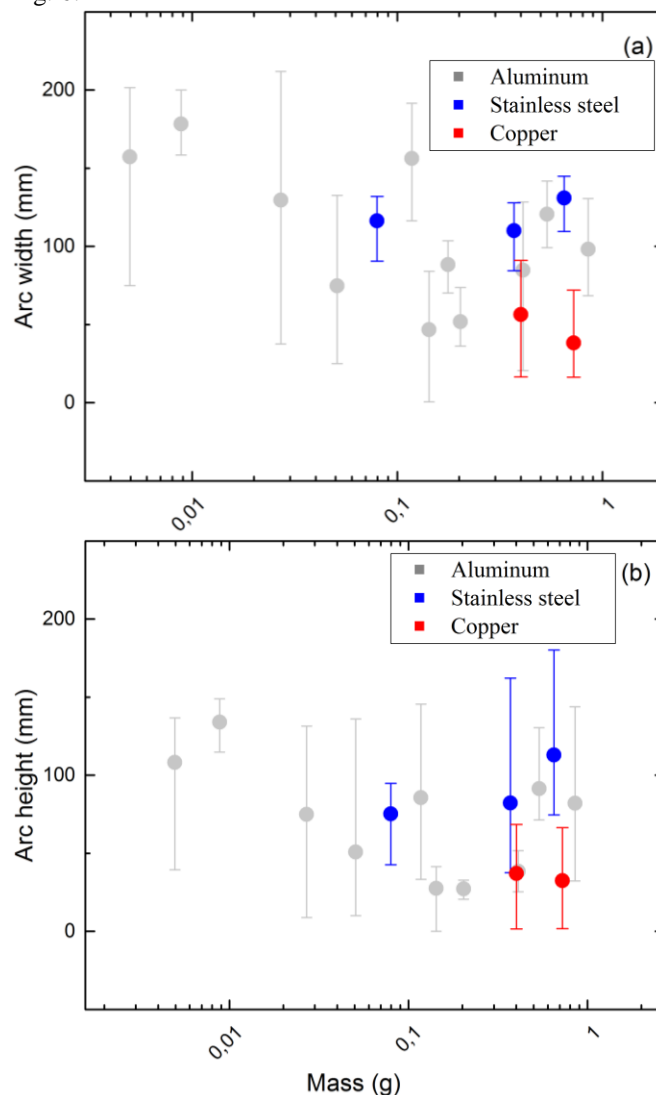


Fig. 5. (a) Arc width and (b) height as a function of the FOD mass. The bars and the point represent the results distribution and the mean value respectively.

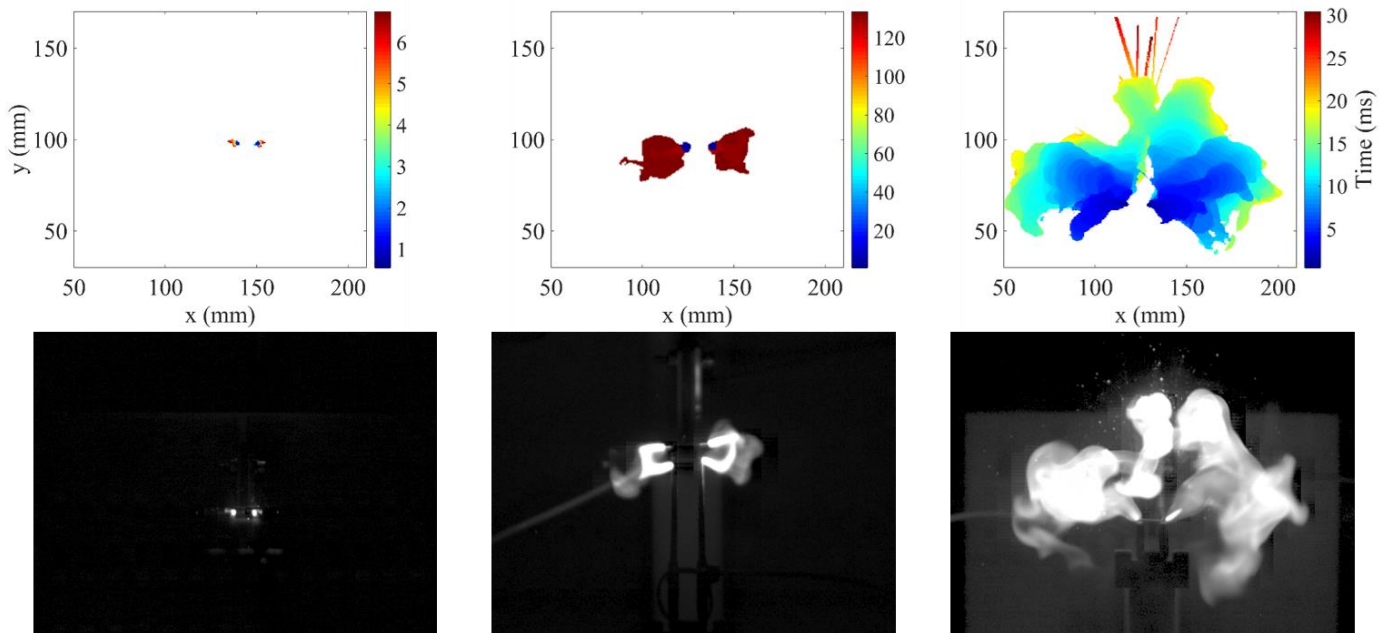


Fig. 6. (top) processed and (bottom) raw images of the electric arc, FOD (left) aluminum 3.12 mm diameter, (center) aluminum 1.92 mm diameter and (right) aluminum 0.7 mm diameter. The processed images correspond to successive integrations of the area occupied by the plasma. The color scale correspond to the time information. The image on the center presents two very distinct color areas, this traduces the occurrence of two arcs, a first one small, leading to the partial ejection of the FOD, followed by a second larger when the FOD fell on the electrodes. On the picture on the right, straight lines can be observed on the top, this is not plasma but the path of ejected molten metal.

The processed images correspond to successive integration of the area occupied by the arc during its whole duration. Several information can be extracted from these images, the maximum width and height taken by the plasma, the total surface and also the area occupied by the plasma at given time thanks to the color scale. The time information is certainly a useful data for the development of active protection, to rule on the available time to extinguish the arc before it reaches a certain dimension and also to quantify the damages induced. The pictures in Fig. 6 confirm that all the arc are not equivalent in size, in order to assess the hypothesis of the correlation between the FOD mass and the arc behavior, the arc maximum width and height are plotted according to the objects mass in the Fig. 5.

As it is possible to observe in the figure above, the hypothesis expressed previously is not verified. Indeed, even if there is a slight decay in the arc width when increasing the object mass, the arc dimensions appear to have a chaotic behavior making it impossible to state on a link with the FOD mass. It is important to note that the same study was performed to analyze if there was a pattern linked to the FOD diameter or metal nature reaching the same conclusion although the metal nature might have an impact on the composition of the plasma [3].

Another important observation is that the dimensions of the plasma can reach very large values, width and height about 20 cm have been observed. Compared to the size of aircraft power distribution systems, an arc this large might damage or be attached to close equipment. In the present study, the depth of the arc is not acquired, however it is planned for further investigation to use another high speed camera to get 3D information of the plasma dimensions.

To conclude on the outputs of the statistical study of the arc behavior, the data to extract in order to design power distribution system is the maximum dimension of the area that can be potentially occupied by an arc and the time the arc takes to reach these dimensions. This gives the available duration to extinguish the arc.

This leads to the second part of the study corresponding to the detection of the arc events thanks to their electrical signatures, in order to design active protection.

### B. Arc electrical signatures

In the first part of the study the arc events were observed thanks to a high speed camera. In this section, the electrical measurements made in parallel are studied to identify the signatures linked to the arc behavior. From the statistical investigation carried out, several event were distinguished:

- Arc ignition
- Arc expansion
- Arc contained
- Arc moving freely
- Arc extinction

While the first and last event correspond to the beginning and the end of the arc, the three others correspond to different arc behaviors.

Three of these events can be observed in the Fig. 7. The event in the picture (1) corresponding to the arc ignition is characterized for the voltage and current by a non-zero value. The electric arc is barely visible at this state. The current amplitude is here limited (about 185 A to 220 A) by the power supply and not by the limiting resistance. In this test, the FOD

was completely ejected leading to a large expansion of the arc. This behavior can be observed in the pictures (2) and (3). From the voltage point of view, it is traduced by a monotonous increase in magnitude and for the current by a decrease in magnitude. The current decrease is likely to be due to the power limitation of the power supply. The current stays pretty stable until the voltage reach a certain amplitude and then starts to rapidly drop until the arc extinction that is observed in the picture (4). In this test it is hard to state weather the arc is extinguished due to the voltage limitation or the power limitation. In the voltage case, the extinction mechanism involved would be the arc expansion until the source wouldn't be able to provide enough voltage for the arc to grow. In the power limitation case, the mechanism could be the decrease in current due to that limit, leading to the arc extinction when the current is not sufficient to sustain the arc.

The next waveform is the one corresponding to the arc contained, meaning that the arc length remains stable over time. The typical waveform associated can be observed in Fig. 8. The voltage wasn't null before the arc because the FOD in this test was ejected by a previous electric arc, the arc in this figure is the one ignited when the FOD fell on the bars. The arc ignition correspond to the picture (1). Only one luminous spot can be observed due to the fact that the object is soldered on one electrode, so only one arc occurred between the object and the other electrode. For the whole arc duration the voltage remain pretty stable (here around 15 – 25 V), this correspond to the image (3), except of the Transient Recovery Voltage (TRV) as in (2). The TRV is a fast rise of the voltage reaching high voltage values. This voltage is not correlated to the arc length as indicated by the image (2) where the plasma area remains small. In this case, the TRV is always greater than the dielectric strength of the medium leading to a reignition at each polarity change [4]. The last waveform observed was the one associated to a free burning arc. This behavior occurred when the arc was no longer attached to the FOD, but moved freely on the electrodes. It generally generates longer arcs (in duration), the arc is initiated at the FOD location, then moves toward the end of the electrodes due to the Laplace force. In order to avoid damages induced by the arc, heat shrink sleeve was placed near the end of the electrodes. Generally, free burning arcs were stopped and then extinguished by the heat shrink sleeve. From the voltage measurement in Fig. 9 it is possible to observe the classical arc ignition and extinction signatures in (1) and (4). On the other hand, the typical waveform of the free burning arc is also visible on the voltage. It is characterized by large variations of the amplitude but, at the contrary of the expansion behavior, the changes in magnitude are not monotonous. This behavior is present before (2) with a steady increase of the voltage and then between (2) and (3) with a sharp decrease of the voltage. This corresponds to a fast motion of the arc that can also be observed in the pictures (2) and (3), where the arc right spot “jumped” from the back to the front of the image.

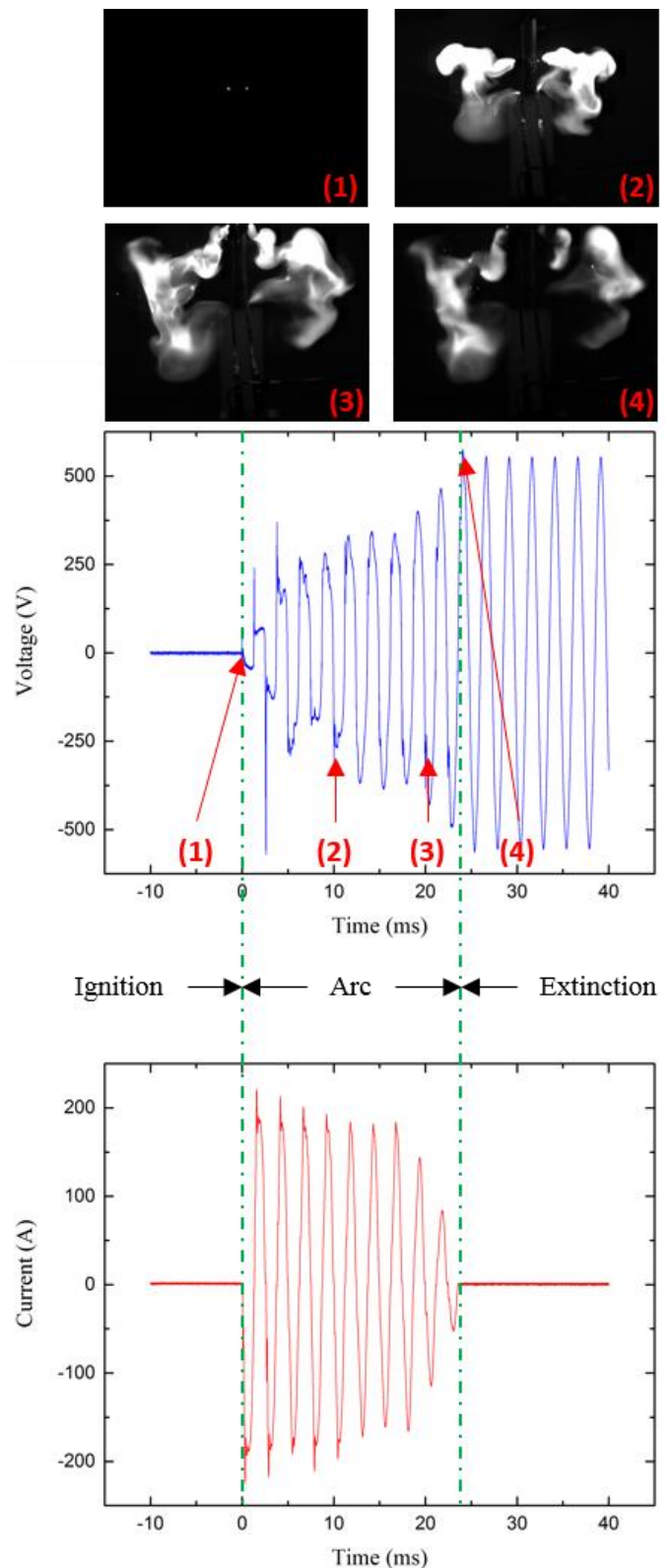


Fig. 7. (Top) Images of the electric arc. (Middle) Voltage measurement. (Bottom) Current measurement. The FOD was aluminum solid wire with 0.7 mm in diameter.

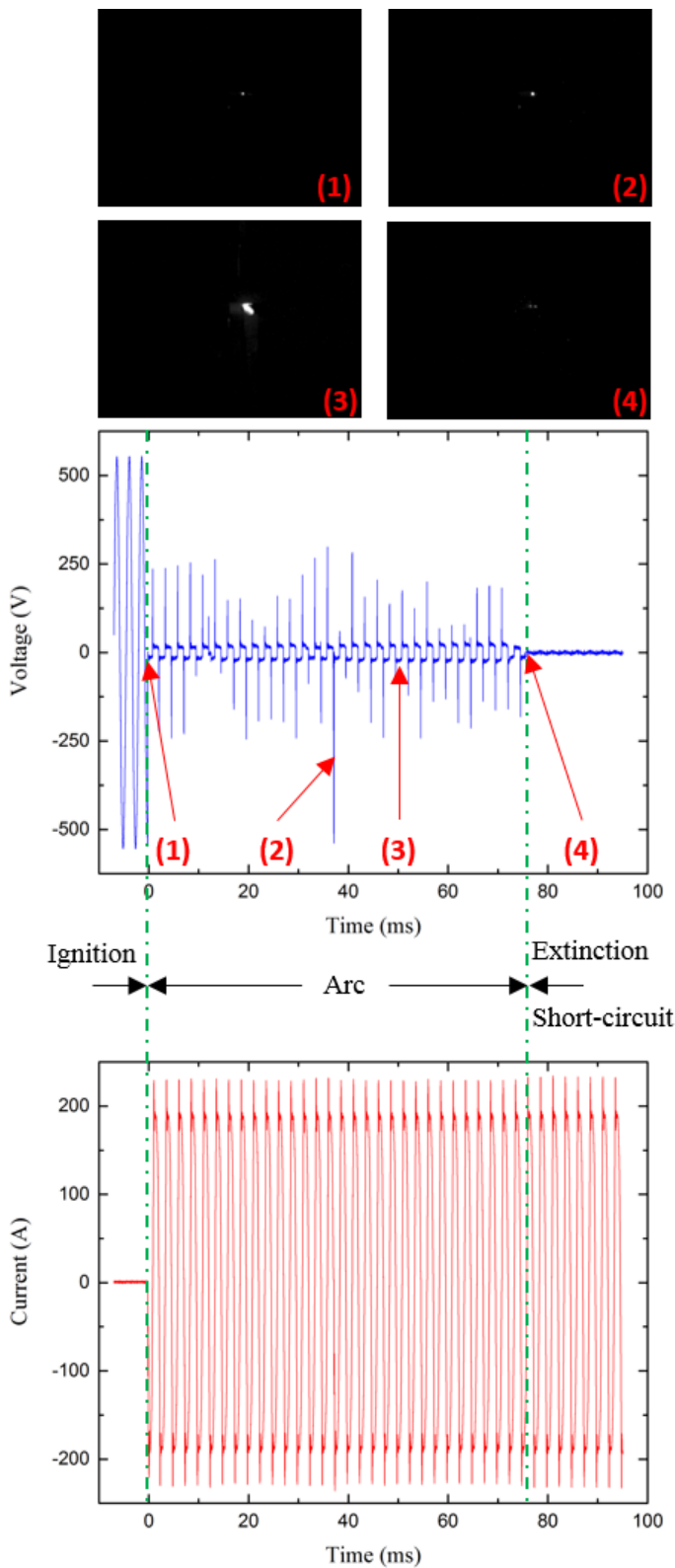


Fig. 8. (Top) Images of the electric arc. (Middle) Voltage measurement. (Bottom) Current measurement. The FOD was aluminum solid wire with 3.93 mm in diameter.

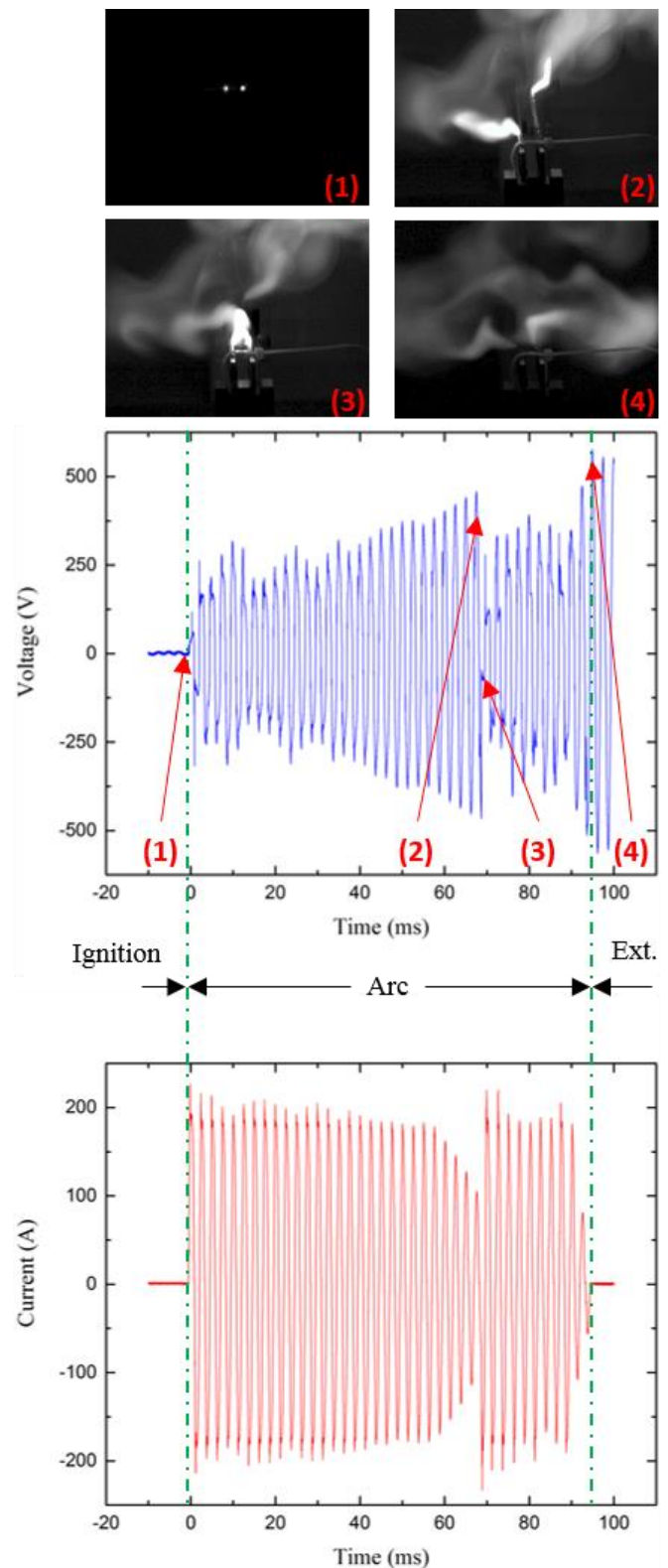


Fig. 9. (Top) Images of the electric arc. (Middle) Voltage measurement. (Bottom) Current measurement. The FOD was aluminum solid wire with 0.4 mm in diameter.

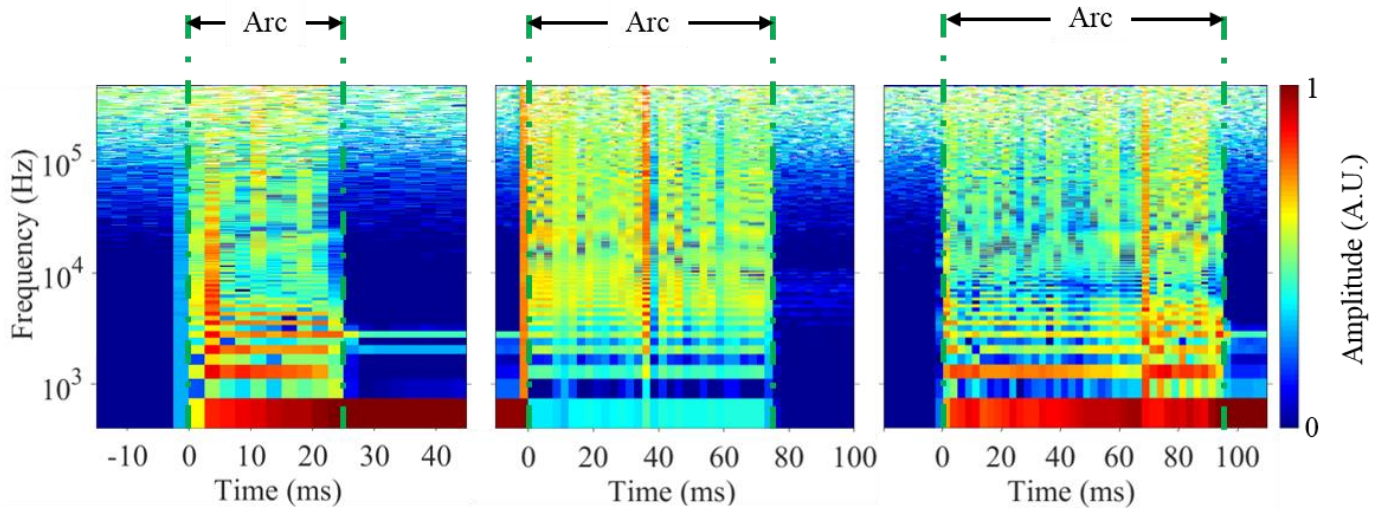


Fig. 10. Spectrograms of the voltage during arc events. The graphs from left to right correspond to the cases presented in Fig. 7, 8 and 9 respectively. The color scale correspond to the amplitude of the  $dV/dt$  in arbitrary unit.

### C. Arc fault detection

The three examples of electrical measurements presented in the previous section prove that typical signatures exist, allowing to identify the arc behavior from the voltage and the current waveforms. If these information bring more tools to understand the electric arc, they cannot help directly to develop arc detection method.

Two difficulties rise when trying to detect arc fault. The variety of waveform generated by the large number of loads present in the electrical network makes complex the detection of arc. Some loads might have an electrical signature very close from the arc one. This leads to the second difficulty, the necessity to avoid false positive. In an aircraft, false positive must be avoided. As can be imagined, the loss of a critical equipment due to a false alarm can be unsafe for the flight.

Current protection devices against arc fault (AFCB and SSPC) are generally based on current monitoring [5]–[7]. A way to avoid false positives and to increase the chances of arc fault detection is likely to be the tracking of multiple arc markers [8]. Some authors also studied the impact of the arc on the voltage waveform for arc fault detection purposes [9].

In order to investigate the impact of the arc on the voltage shape, the frequency content of the  $dV/dt$  was extracted before, during and after the electric arc. The spectrograms, plotted in Fig. 10, were obtained thanks to Fast Fourier Transform (FFT) applied on windows with 2.5 ms duration, corresponding to one period of the signal. The arc signature is clear from the three spectrograms, before and after the arc, the frequency content of the signal doesn't span above 2.6 kHz, whereas during the arc it spans above 100 kHz. In the present case, using the frequency analysis of the  $dV/dt$  would allow differentiating the electric arc from the zero voltage, open circuit and short circuit.

To validate the reliability of the  $dV/dt$  frequency content as one of the relevant markers of the electric arc, it would necessitate to carry out arc tests initiated by FOD with different kind of loads connected in parallel and/or in series

and also to use electrical sources more representative of aircraft power generation.

## IV. CONCLUSION

The electric arc initiated by a FOD in aeronautical conditions has been studied. From the statistical study of the FOD behavior it was determined that a transition occurred between the object being ejected and welded on the electrodes when increasing the mass of the object. The hypothesis that the object behavior would impact the arc dimensions was invalidated thanks to the characterization of the arc length and width from the high speed camera acquisitions. As the FOD mass and nature didn't seemed to impact the arc damaging potential, it appears to be difficult to give guidelines for the design of a mechanical protection for aircraft power distribution systems. From this consideration, the need for active protection was confirmed.

Three main conclusions can be drawn from the present study. In order to determine the time in which a protection device should be able to detect and secure a system, the analysis of the arc dimensions over time, compared to the dimensions of an aircraft power distribution system can provide very interesting data. If detected, the arc behavior can be identified from the voltage waveform. This information can be useful as the arc damaging potential differ from a contained arc to a free burning arc. The best strategy for the detection of the arc with the higher success ratio and the less false positive detection is likely to be achievable thanks to the monitoring and comparison of several arc electrical markers or even other type of markers. Even if generally the studies focus on the current, the voltage contains many information on the arc and the  $dV/dt$  frequency content seems to be a relevant marker of the arc.

Further steps of this study include carrying out this experiment in presence of other system parts close to the electrodes to determine the behavior of the arc and using two high speed cameras to get volume information on the arc.



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