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INFLUENCE OF CONFIGURATION EFFECTS ON "MULTIPLE BURST" SIMULATION TESTING

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ABSTRACT

During the initial phasis of a lightning strike attachment on an aircraft, fast current pulses (rise time ≈ 100 ns, Imax ≈ few kA) have been measured, which can create equipment upsets or disturbances. This threat, made of repetitive pulses and usually called "multiple burst", can be reproduced at the equiment interfaces assuming that the transfer function of the structure was determined. The normalized waveform H (10kA - 100 ns rise time) is the reference for one of these pulses.
This paper emphasizes the importance of the coaxial return path termination for the injection of the wave H. According to the constitutive materials of the test-bed, and the adaptation of the line, the natural oscillations of the structure and the internal coupling mechanims can be modified. As a conclusion, various test configurations in relation with the nature of the test-bed and the characteristics of the generator are detailed, for a more accurate ground simulation of the attachment phasis.

I - INTRODUCTION

The document SAE-AE 4L "ORANGE BOOK" suggests the following scenario for the attachment process : for each attachment or reattachment, a series of 20 pulses of current (waveform H) is flowing in the external structure with a repetition frequency between 20 and 100 kHz. It is mentioned that 24 bursts of 20 pulses (total of 480 pulses) can occur in a lightning event during a total duration time of 2 s.
The analysis of the results of "in flight measurements" (TRANSALL - CV 580) made by the ONERA ("Office National d'Etudes et de Recherches Aérospatiales" - FRANCE : in flight programme supported by the MOD/DGA) suggests another scenario [Ref. 1] : the multiple burst sequence could only appear 2 or 3 times maximum during the lightning flash, and Mr MAZUR explained in the ICOLSE 88 conference of OKLAHOMA that one attachment only was likely to occur for the stepped leaders.

We can however notice that there is a consensus about the characteristics of the waveform H, with the restriction that rise time of 60 ns have been recorded.
Whatever the number of pulses, it is clear that it will be impossible to drive n pulses of m bursts on a whole aircraft ! It would require n x m Marx generators from about 800 kv, sucessively triggered. The demonstration method chosen by the C.E.A.T. consists in determining the tranfer function of the various bundles for a single excitation of a H pulse on the whole aircraft, and then to test the inside equipments at low level (2000 V.) with the repetition rate specified (arbitrary waveform synthesizer + pulse amplifier).

II - NATURAL RESONANCES

1°) When studying the data of in flight measurements, we can notice that natural resonances of the structure are excited. For exemple, on the F 106 [NASA-Ref 2] the measurements of dD/dt show oscillations at 7 MHz and 21 MHz (L = λ/2 = 14 m → Fr = 10 MHz) and the dB/dt leads to 7 MHz only. The oscillation at 21 MHz is preponderant on the nose current. On the TRANSALL [Ref 3] the oscillation is about 5 MHz (very near to the fuselage resonance of the aircraft). Nevertheless, no information is given about the damping factor of these oscillations. A theoretical analysis with a 3 D code (Integral method) [Ref 4], on a model representing the central part of the fuselage with its 2 wings, shows the superposition of two main resonances λ/2 and λ/4 (lightning strike from one wing tip to the other wing tip).
In short :

Resonance	IN FLIGHT	3D MODELING
Wing	---	λ/4 - λ/2
Fuselage	λ/2 - 3λ/2	---

Table I : strutural resonances

2°) Classical test set-up for the ground simulation :

A coaxial return path is built around the structure of the aircraft to ensure that the repartition of currents on the skin is the same as it would be in free space, during a lightning strike (Fig. 1)

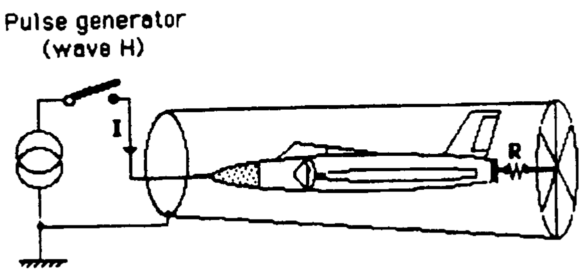


Figure 1. Usual test set-up

To prevent parasite reflections, the inductance (µH/m) of the transmision line will be as constant as possible. But the same question remains for the simulation : what appropriate mismatching must be recreated and how to reproduce the in flight oscillations ?

It is obvious that the induced effects on the internal wirings are strongly correlated to the possible oscillations and their damping factor. That's why 2 different values of load resistance R were chosen :

First case : R = 0 (short-circuit = usual test set-up configuration for very high current injections)
Travelling waves (f= c/4l) are going to pile on the bi-exponential current delivered by the generator. The frequency spectrum of the normalized wave H is strongly modified at the frequencies corresponding to $l = \lambda/4$ and $l = 3\lambda/4$

Second case : R = Zo (characteristic impedance of the coaxial return path)
Except some discontinuities of the aircraft geometry, the line is matched, and the natural structural oscillations are not excited. The frequency spectrum of the normalized wave H is not modified.

III COUPLING ON TYPICAL WIRES FOR BOTH CONFIGURATIONS (short circuit load and matched load)

To quantify the importance of the resistive load R, this paragraph summarizes the results achieved on 3 different test-beds

III 1 - "ECUREUIL" helicopter :

In the frame of the joint venture programme AFARP 17 (Anglo French Aeronautical Research Programme), different tests (CW - High voltage test - High current injections) have been performed on the structure of a helicopter (with large dielectric parts). A view of the test set-up is given on fig. 2, for the high current injection phasis.

Figure 2. "ECUREUIL" Helicopter in the coaxial return path (Zo=60 Ω)

The comparison is performed for the single wire L4 located in the aluminium tail, between the rear rotor and the equipment bay (length = 10 m = 33 ft)
Table II. presents in time and frequency domains the characteristics of the induced levels (for I injected = 1 kA waveform H/10)

COAXIAL RETURN CONFIGUR.	OPEN CIRCUIT VOLTAGE L4 Voc		SHORT CIRCUIT CURRENT L4 Isc	
	Max Level	Main Fr.	Max Level	Main Fr.
Matched R = 60)	180 v	7,8Mhz 22 Mhz	1 A	6-12Mhz 22Mhz
Short Circuit (R = 0)	230 v	4,3Mhz 7,8Mhz 12 Mhz 22 Mhz	1,5 A	5,4Mhz 6,3Mhz 12 Mhz 22 Mhz

Table II.Induced levels on the line L4 (10m) for I injected = 1 kA (H/10)

• Resonances of the structure of the helicopter : (l = 16 m = 52 ft)

$\lambda/4$ = 4.3 MHZ
$\lambda/2$ = 8.6 MHZ
$3\lambda/4$ = 12.5 MHZ

*Resonances of the wire L4 (l= 10m = 33 ft)

$\lambda/4$ = 7.8 MHZ

$3\lambda/4$ = 22. MHZ

In table 2 and fig. 6b we can notice that :

- The maximum levels are measured in the short-circuit coaxial return path (the ratio is however < 2)
- The energy at the frequency corresponding to $\lambda/2$ of the structure is very low (8,6 MHZ)
- Resonances at the quarterwave length and $3\lambda/4$ of the structure are strong but the coupling on the line at these frequencies is only clear on the short circuit current.
- Same level of energy corresponding to $\lambda/4$ and $3\lambda/4$ of the wire itself for both configurations. (we can notice that the capacitance of the line decreases the frequency of the resonance)
- The transfer fonctions Vco/Iinj are different according to the load R. (Fig.)
  - Short circuit line = extrema for $\lambda/4$ and $3\lambda/4$ of the structure and, $\lambda/4$, $3\lambda/4$ of the wire itself.
  - Matched line = extrema only for $\lambda/4$ and $3\lambda/4$ of the wire itself

The source impedances Z_g = Voc/Icc of the generator equivalent to the cable are the same for both configurations (fig. 6a).
It varies from 1Ω to 300Ω between 50 kHz and 2MHz, and can increase 10 kΩ for the resonances mentioned above. This parameter, dependent on the position of the wire in the structure, is not depending on the test condition [Remark : for F → 0, Z_g → ohmic resistance of the wire]
In short, the frequency responses can be simplified as follow :

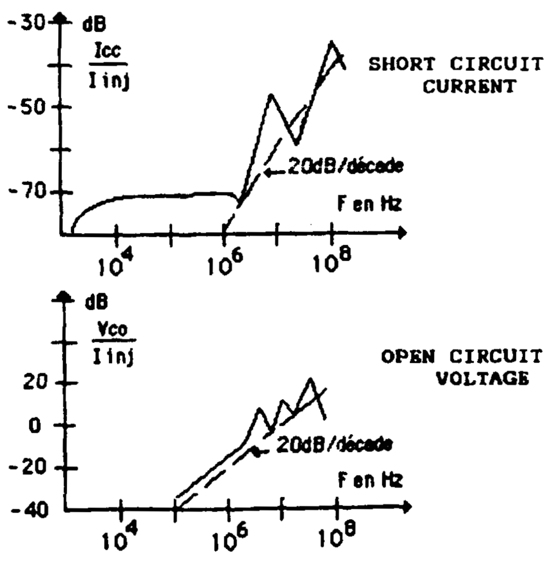


Figure 3. Transfer functions (short circuit current - open circuit voltage) for a wire in an aluminium structure

III 2 - CARBON FIBER WING "V.C.C."

III 2-1- : Without coating mesh :

Characteristics : L = 5m (16ft)

Z_s = 20 mΩ.□

R total = 16 mΩ

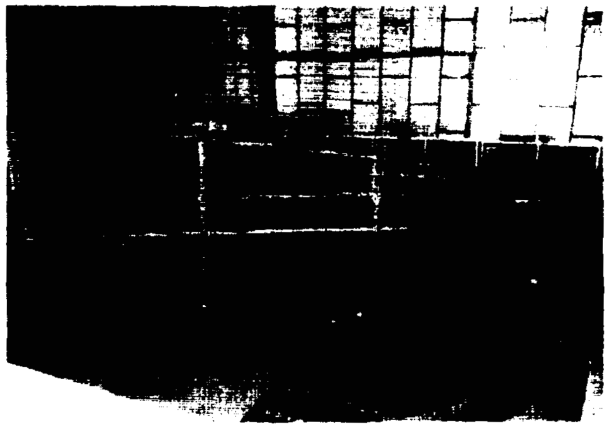


Figure 4. Wing "VCC" in the coaxial return path

On a single wire located in the center part of the wing (E field not significant), the following levels have been measured for Iinj = 1kA (H/10)

COAXIAL RETURN CONFIGUR.	OPEN CIRCUIT VOLTAGE Voc	SHORT CIRCUIT CURRENT Isc	
R= 60Ω	Max Level 28 V peak 8,5 Mhz	Max Level 13 A no oscill.	bi-expo.wave tm = 8 µs td =30 µs
R= 0Ω	29 V peak 8,5 Mhz	13 A no oscill.	bi-expo.wave tm = 8 µs td =30 µs

Table III : Induced levels on a wire (L = 5m) located in the center part of the carbon fiber wing (without mesh) for Iinj=1kA (H/10)

We can notice here, that no excitation corresponding to the natural resonances of the structure (wing) is visible, contrary to the case of the helicopter part in aluminium. The only resonance measured is the one of the wire itself (8.5 MHz)
So, in this case, the test configuration has no influence on the induced levels, which are identical. (Fig.7b)
This result is fundamentally different from the previous one concerning the aluminium structure of the ECUREUIL (§ III 1)
It's important to look at the waveform of the induced short circuit current (Fig.5): the injected waveform is a 0.1/4µs wave and the induced wave is a 8/60µs wave. The carbon fiber skin acts as an integrator (1st order filter with fc < 10 kHz), which leads to an important delay between the two waveform peaks :

$$I_{cc} = K \int V_{oc} \cdot dt$$

The ratio of the extrema (Fig. 5) of the values of Voc and Isc has no physical meaning. Only the integral $1/4\int Voc.Icc\ dt$ can be interpreted as the maximum energy that the wire will be able to deliver on a terminal load.

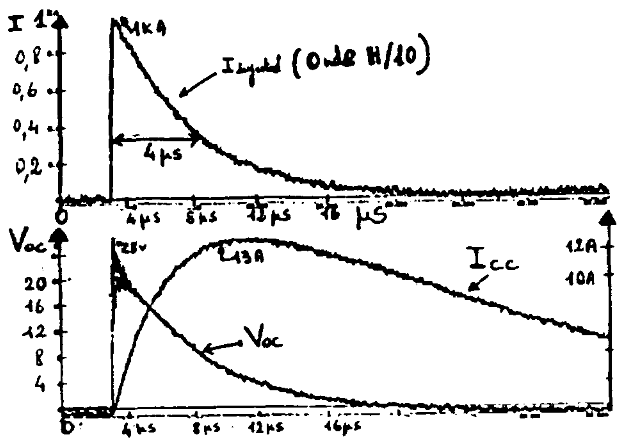


Figure 5. Iinjected current Isc and Voc waveforms

III 2-2- Carbon fiber wing covered by an aluminium mesh :

The same wing (as in & III.2.1.) was covered by a mesh : Zs = 3 mΩ.□
The total resistance of the wing Rt=7.8 mΩ

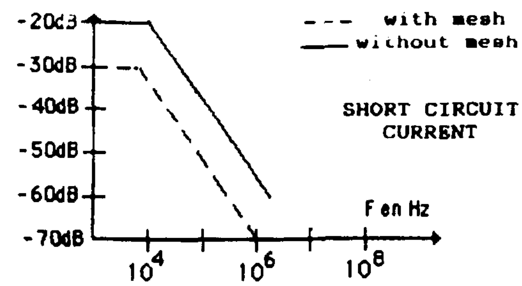
	OPEN CIRCUIT VOLTAGE Voc		SHORT CIRCUIT CURRENT Isc	
	Max Level		Max Level	Long wave
R= 60 Ω	14 V Peak 8,5 Mhz	L.F.= 6 V H.F.= 8 V.	4 A.	tm = 8µs td = 30µs
R= 0 Ω	12,9 V peak 8,5 Mhz	L.F.= 6 V. H.F.= 6 V.	3,5 A.	tm = 8µs td = 30µs

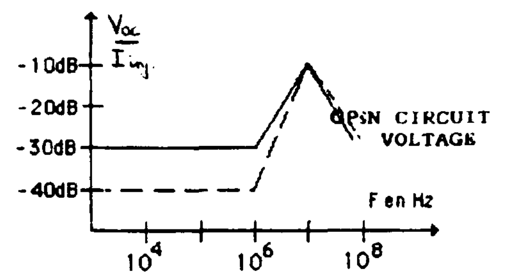
Table IV : Induced levels on a single wire (5m) in the center part of the wing covered by alumesh (wave H/10).

By comparison of the tables III, IV and Fig. 8 we notice the following important results :

- Same internal behaviour of the wing, whichever the coaxial return load is used. The transfer functions are given below : the shielding effect of the mesh is only evident below 1 MHz on the voltage transfer function (-10dB). We have to bear in mind that the main reason for the use of a mesh is the protection of the fuel tank against the direct effects (burning through) and not to achieve high attenuation levels.

A summary of the typical transfer functions on a wire in a carbon fiber structure is given below :





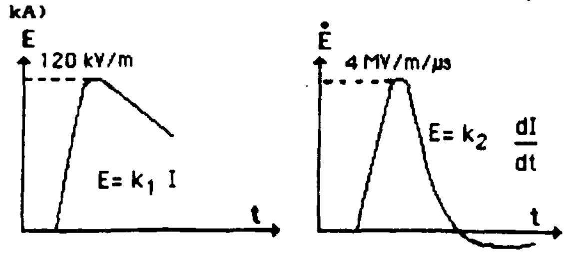
The shielding effect of the mesh is about -10 dB between 10 khz and 1 MHz (Fig. 9)

IV- INFLUENCE OF THE ELECTRIC FIELD ASSOCIATED TO THE CURRENT

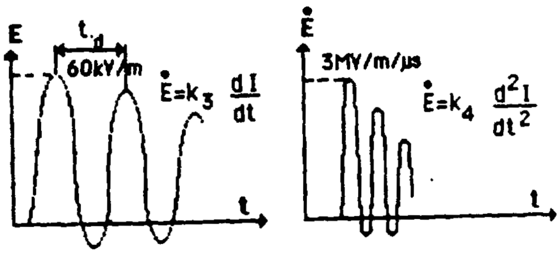
A high voltage generator is necessary to inject the current waveform. So, an important electric fied raises in the coaxial return. The previous analyses were performed on wires located in areas where the electric field was insignificant, that means without any effect.
But, more generally, the extrapolation of the signals to the threat (D/10 → D and H/10 → H) requires a precise analysis to separate the electric coupling from the magnetic coupling. This is particularly true for the wirings exposed under open structures (dielectric fairings). The two test set-up above mentionned lead to a different electric coupling.

• matched coaxial return :

The values of E and dE/dt on the extrados of the wing are constant along the coaxial return. An idea of the levels is given below for H/10 wave - (1 kA)



• **Short-circuit coaxial return :**
The values of E and dE/dt are not constant any more along the line : maximum at the entry and zero at the end of the line. The following diagrams show the waveforms recorded at the input of the transmission line (for H/10) ;

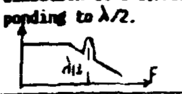


For a test at H level (10 kA), the order of magnitude of dE/dt is 10^{13} V/m/s, close to the values of in flight measurements [Ref.3] Although it is controlled by the current parameter, the simulation in a coaxial return gives a proper electrical excitation, by comparison with the levels encountered in free space (excitation not yet normalized)

REMARK : A test configuration can help, in some cases, to determine the type of coupling (E or I) and thus enables the extrapolation method : by creating a second arc channel at the end of the coaxial return, the electric field is maintained till the connection of this gap (few µs) and then a negative dE/dt is appearing, though I and DI/dt are positive. An inversion of polarity on the induced voltage, due to the subsequent effects of E and I is visible.

V - CONCLUSION

This paper reminds us of the influence of the type of return load used (matched or short circuit) on the levels and frequency spectrum of the induced transients. According to the nature of the structure, a test configuration is more suitable to recreate the real threat.

Nature	Structure	Resonance (In flight)	Test set-up Extrapolation method
Metal	wing	λ/4 3λ/4	-short circuit coaxial return. Wave H(10kA) -If excitation by an homothetic reduced wave, extrapolation by scaling factor
	fuselage	λ/2	-matched coaxial return. Wave H(10KA) -For the extrapolation add to the spectrum of the wave H, an oscillation at f corresponding to λ/2. 

Nature	Structure	Resonance (In flight)	Test set-up Extrapolation method
Carbon (with or without mesh)	Wing	λ/4 3λ/4	- Short Circuit or matched coaxial return (indifferently) Extrapolation : see 1 st case
	Fuselage	λ/2	- Short Circuit or matched coaxial return (indifferently) Extrapolation : see 2nd case
Carbon • metal	Wole Aircraft	See § II-1	- To analyse, according to the quantity and location of metal parts and convenient possibilities for the realisation of the test-bed.

The generator must be able to inject the normalized current waveform. That's why the C.E.A.T. has given the following specifications for its new facilities.

* Marx generator (8 stages of 100 kV) with low internal inductance L < 2 µH and a coaxial output Z = 60 Ω)
* Two biexponential waves will be possible :
  - -H : Imax=10 KA tm = [60,100ns] t 1/2 = 4 µs
  - -D/2 : (with crowbar) Imax = 50 kA tm= 1µs t1/2 = 35 µs

The results of the V.C.C. (Voiture Composite Carbon = Carbon Composite Wing) come from a joint programme C.E.A.T. / AEROSPATIALE / DASSAULT AVIATION supported by DGAC and DGA/ DCAé/STTE

DGAC = Direction Générale de l'Aviation Civile
DGA/DCAé/STTE = Délégation Générale pour l'Armement . Direction des Constructions Aéronautiques. Service Technique des Télécommunications et Equipements Aéronautiques.

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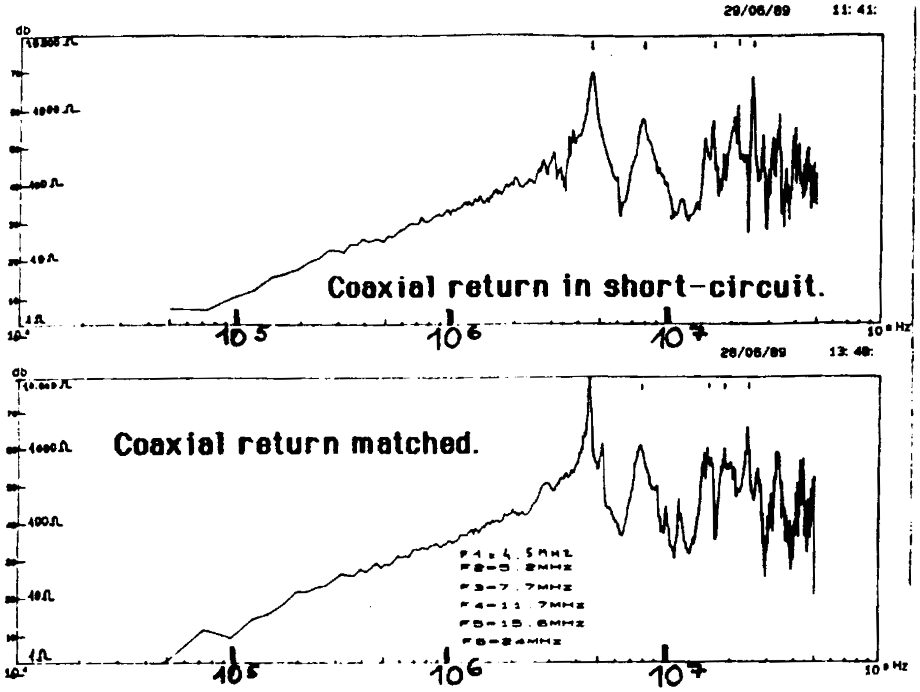
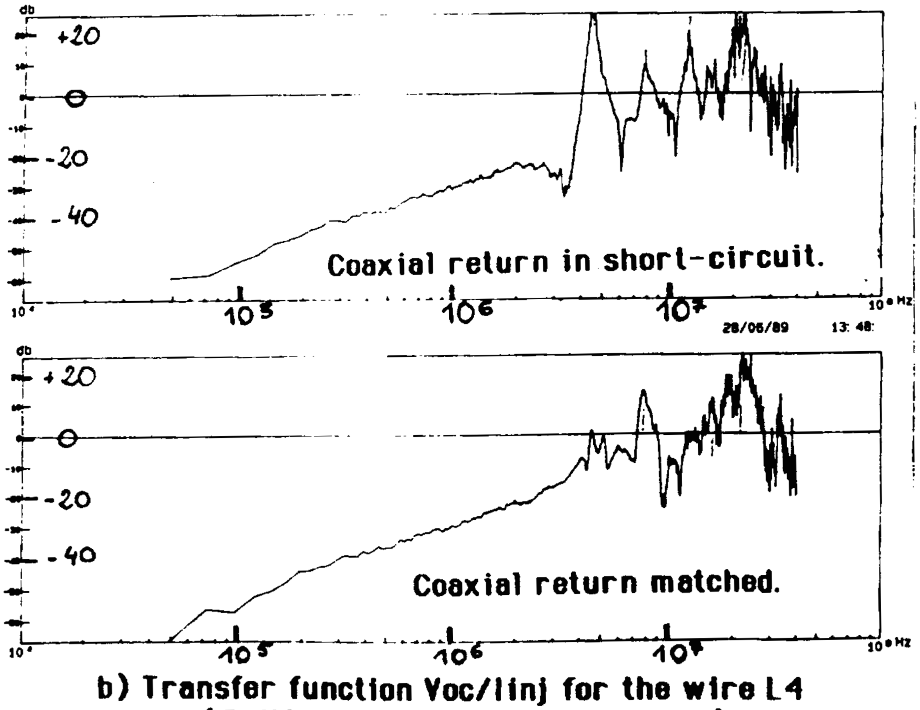
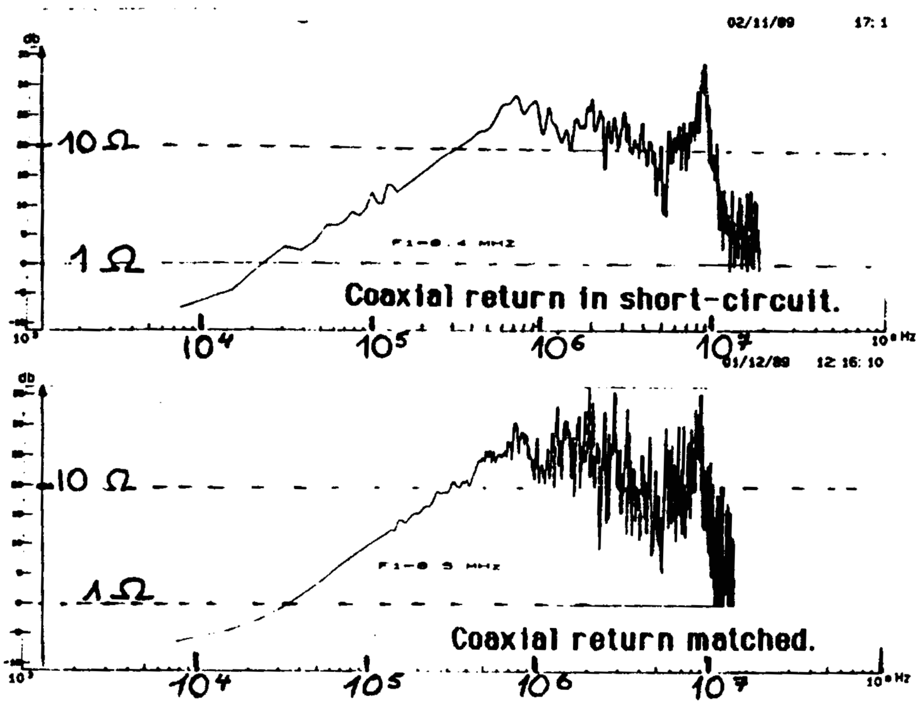


a) Source impedance Zg=Voc/Isc of the generator equivalent to the wire L4
(Coaxial return in short circuit or matched)

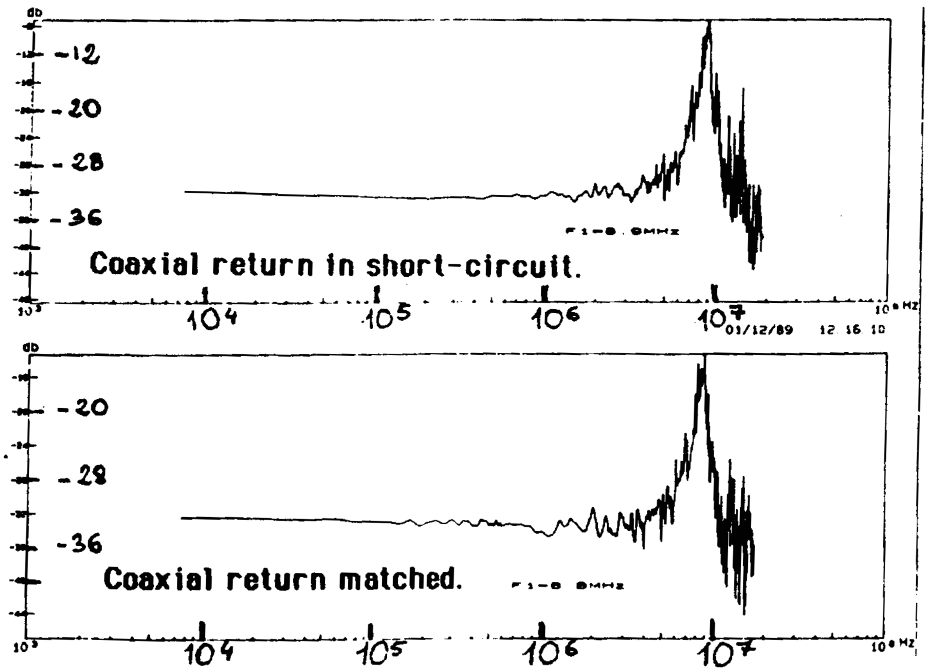


b) Transfer function Voc/Iinj for the wire L4
(2 different coaxial return loads).

FIGURE 6 : SINGLE WIRE BETWEEN THE TAIL ROTOR AND THE EQUIPMENT BAY OF THE HELICOPTER "ECUREUIL" FROM AEROSPATIALE (As 355).

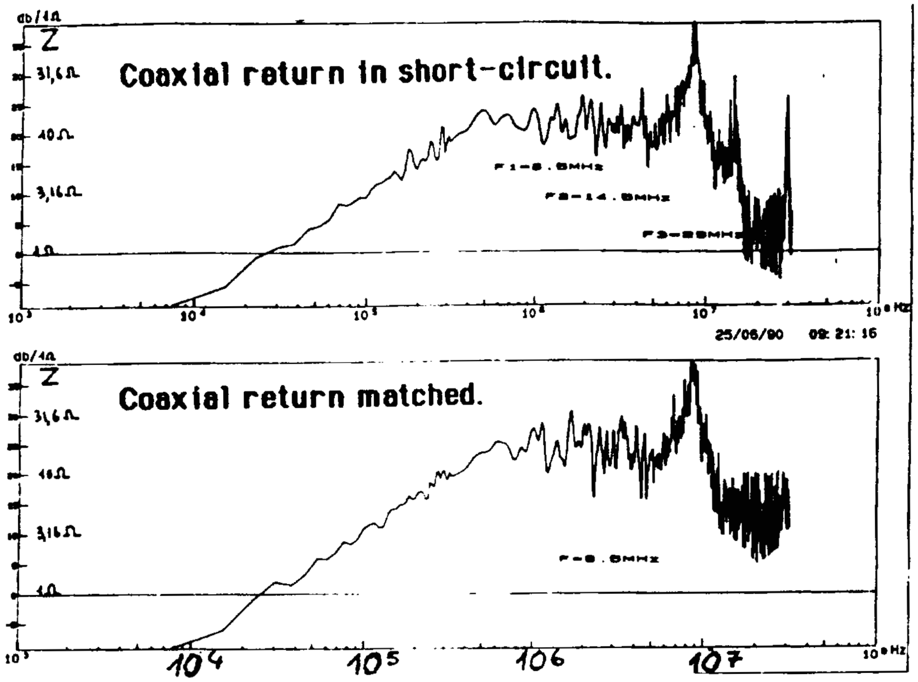


a)Source impedance Zg=Voc/Isc of the generator equivalent to the wire B2A
(Coaxial return in short-circuit or matched)

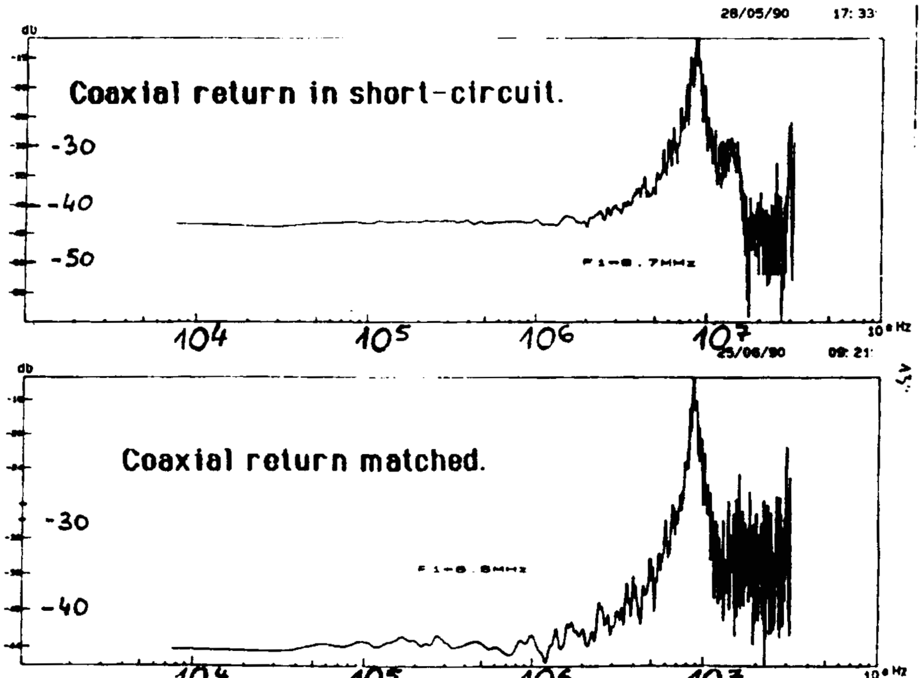


b) Transfer function Voc/Iinj for the wire B2A
(2 different coaxial return loads).

FIGURE 7 : COMPOSITE CARBON WING (VCC) WITHOUT MESH.

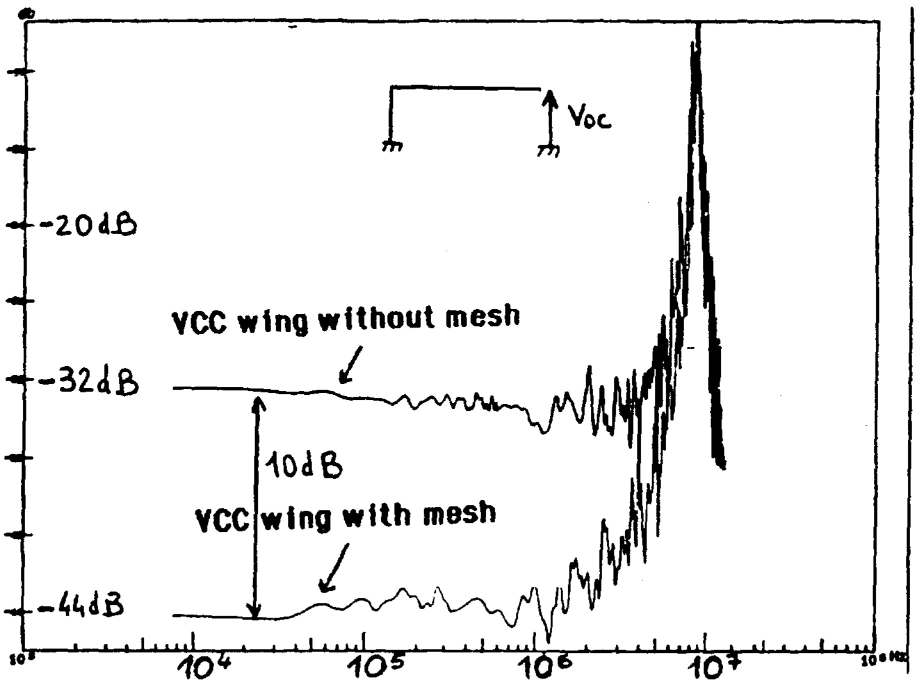


a)Source impedance Zg=Voc/Isc of the generator equivalent to the wire B2A
(Coaxial return in short-circuit or matched)

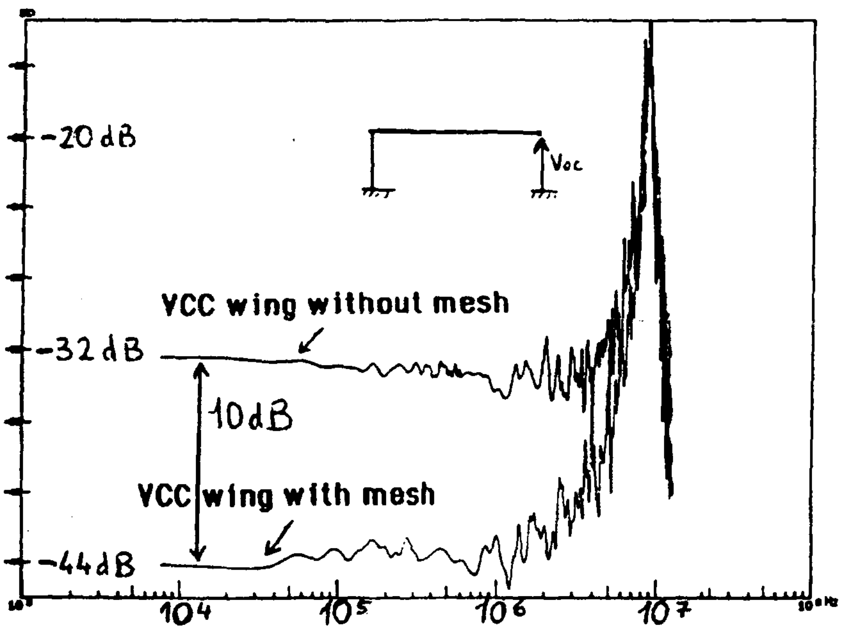


b) Transfer function Voc/Iinj for the wire B2A
(2 different coaxial return loads).

FIGURE 8 : COMPOSITE CARBON WING (VCC) WITH MESH.



Coaxial return in short-circuit.



Coaxial return matched.

Transfer function Voc/Isc for the wire B2A of the carbone wing with and without mesh for both values of return load .

FIGURE 9