Aerodynamical Performance Decay Due to Fouling and Erosion in Axial Compressor for GT Aeroengines

*Giovanni Maria De Pratti**

“La Sapienza” University of Rome, DIMA

Abstract. The ingestion of solid abrasive particles and/or foulants causes erosion of the compressor blades, resulting in a considerable reduction in the performance and working life of aviation/heavy duty GT and an increase in fuel consumption. The geometry variation at the Leading Edge (L.E. blunting) and Trailing Edge (T.E. thickness reduction), together with the general increase of airfoil surface roughness, depends on the characteristics of the incident particles, the geometry and the materials of the blade cascade, the dynamic parameters of the particles and on the type of impact. In order to rectify this degradation in performance, it is therefore necessary to re-profile the blades with machining that is highly critical for the performance of the engine, the life of the compressor blades and for maintenance costs. In order to determine an optimum and cost effective process of re-profiling, a series of tests reproducing the corresponding models of flow have been carried out on the Water Table Test Bench using Lamb's hydraulic analogy relative to profiles of the VII and VIII stage HP of the compressor of the GT CF6-50 (G.E. Co.). The tests were carried out both on the isolated airfoil profile and on the blade cascade and both in the original conditions, at varied geometry (because of erosion and/or fouling) and after re-profiling. The trajectories of the particles have been visualised in several ways (like a false color photographic procedure), confirming results reported by various authors related to the model of impact and erosion. Particularly in the case of the dust aspiration during the arrival phase on the deck of an aircraft carrier. The test results have been discussed and compared with those available in scientific literature.

* Corresponding Author: giovannimaria.depratti@uniroma1.it

1. Overview

The performance of the axial compressor blades of gas turbine engines basically depends on the shape of the profile of the airfoil and especially on the design of its leading edge (both shape and incidence angle).

According to [2], "...there is a small correlation between the chord length and the geometry of the blade. The radius of the leading edge (L.E.R.) and its incidence have a larger influence on performance than the chord length".

The shape of the blades, optimized during the design phase and the construction of the compressor, undergo significant changes during operation; possible flaws or modifications that can arise during operation cause a drop in aerodynamic performance which then results in an increase in fuel consumption and a lower engine "efficiency", as well as increasing the maximum temperature of the cycle (E.G.T.).

Furthermore, during a quality inspection, the "damaged" blades can be discarded, which results in an increase in costs and a loss in materials. There are a number of types of imperfections and variations of the profile of the blade sections, described in detail in scientific studies [cfr. in [2], [22], [12], [23], [6], [7], [15], [14] and [16], such as:

- 1) leading edge erosion (blunting and variation in the incidence angle and in the leading edge radius);
- 2) thinning of the blade trailing edge;
- 3) variation of the blade trailing edge angle;
- 4) increase in surface roughness
- 5) camber variation.

Erosion can reach significant values and effects depending on the large amount of dust contained in the high inlet flow rate. These dust particles can be of various types, from sand to ash of volcanic origin, or salt spread on the icy runways etc. On the other hand, it is not only dust that causes damage to the turbine and compressor blades. In general, according to [14], a drop in performance of the gas turbines is due to a series of various causes:

a) fouling (caused by minute dusts: pollen, salt spray and insects which are deposited on the surfaces);

b) erosion (of the blade surface caused by solid particle ingestion);

c) increase of the gap at the tip of the blade (caused by solid particle ingestion);

rain drop ingestion;

d) damage from foreign objects (FOD) (caused by hail, gravel from the runway and avian ingestion.

In a previous paper [10] some aspects shown by [7], [8], [14], [22] and [15], and, finally, they have recognised as a number of aircraft incidents and failures caused by solid ingestion of various kinds, an indication that the problem has repercussions on the safety and reliability of the use of aviation gas turbine engines (flight safety). The vulnerability of high performance aircraft and of gas turbines of stationary power installations to particles carried in the intake airflow is a highly serious issue which concerns both manufacturers and users of these turbo machines, regarding construction with suitable materials for manufacturers, and the fine tuning of adequate procedures of maintenance and restoring for both manufacturers and users. The damage also has complex economic implications concerning both management and maintenance: regarding plant management, [22] reports, for example, that the leading edge blunting can cause an increase in fuel consumption of 0.38%, while the increase in surface roughness causes an extra 0.19% increase in fuel consumption. Data from ICAO and IATA shows considerable sensitivity on the part of airline carriers to the problem of the weight of fuel costs on airline management, even when low. [9] reports that for a “typical airline” the percentage rate of the total operating costs of fuel and lubricants is 13.9%, while the cost of the fleet’s aircraft maintenance is 10.9 %. Clearly erosion and the subsequent performance degradation of the compressors and consequently of gas turbine engines, is connected to this argument of operating efficiency and of maintaining the engines in flight as long as possible and in safe conditions; and it is equally clear that a reduction in fuel consumption and maintenance costs can benefit the carrier’s budget.

Starting from the year 2000 (source: IACO) the critical situation of a number of airlines has also been attributed to fuel costs and aircraft maintenance costs, besides the costs of employees.

According to [16], in a typical gas turbine power plant, 50-70% of operating and maintenance costs comes from repairing and substituting the major components in the hot section of the gas turbine, and we know that the deterioration of the blades also causes an increase in maximum temperature (E.G.T.). [16] also reports that damage caused by FOD accounts for a minimum of 10% and maximum of 30% of parts to be replaced, and causes various degrees of damage classified as: “minor”, “medium” and “major”. This broad overview gives a very clear picture of the number of damages to the compressor blades and the wide range of situations to be dealt with. Stationary applications benefit from complex filter devices but, as [12] [13] [20] and [21] report, particles with a diameter of under 15 μm are difficult to separate in cyclones. Both researchers cite Montgomery & Clark’s data from 1962, according to which, particles with a diameter under 5 μm can cause serious losses during the operating life of gas turbines.

2. Reference Data

The range of the most commonly used gas turbine engines is very wide and varied and in this regard [12] compiled a table, reproduced below (Table 1), which records the sectors covered by various manufacturers. Regarding these small aeronautical turbines, [1] states that “...the performance...[of these machines]...can be much more susceptible to fouling than their industrial counterparts...”.

Table 1.

Manufacturer	Unit	% of Market
ASEA Brown Boveri GT – 8, 9, 11,13	550	10
GE. Co Frame 5, 6, 7, 9	3,500	64
Siemens/KWU V64, 84, 94	150	3
Westinghouse W 171-501	1,300	23
Total (the values are approximate)	5,500	100

[5] cites studies carried out on the P/W TF33P11A turbofan and the P/W J57-19W turbojet, while [19] cites studies carried out on the TF-39 and the F-100, two engines for military aircraft (for transport and combat respectively). [10] cites some studies carried out on the JT8D and [14] refers, on the other hand, to those on an automotive engine of the Chrysler Corporation. [1] carried out their evaluations of two common pipeline engines, the G.E. LM2500 and the Solar Centaur. [14] report data regarding the Pratt & Whitney JT9D and the General Electric Company CF6. The latter, the G.E. CF6-50, is the gas turbine engine that we have taken as a point of reference for our investigation. It is a turbofan installed in a "wide body" aircraft such as the Boeing 747 and the Airbus A300, which are widely used aircraft and are still used by numerous airline carriers. Some suitably modified versions have also been used in stationary applications. The full name of the engine is GE CF6-50 High by-pass Turbofan Engine and its reference details are shown in Table 2.

Table 2.

Thrust	50,000 lb (222,221 N)
Total Length	246.3 in (6.256 m)
Total Weight	8,756 lb (3,979.3 kg)
Direction of Rotation	Clockwise

The engine has a low pressure compressor (LPC) with a fan and booster, and a high pressure compressor (HPC) composed of 14 stages, of which the first seven have adjustable statoric guide

vanes). It has a pressure ratio at 29.3. This compresses the air up to 2.758 MPa before it is sent to the combustion chamber. Regarding stages 7 and 8, especially stage VIII, of the high pressure compressor, tests have been carried out to establish the aerodynamic performance of the isolated airfoil profile in original profile conditions, as well as worn and restored in at least two modes, that is through grinding and in similitude conditions. The type of isolated airfoil profiles has been derived from the original designs of the engine and its better designation may be Gottinga profiles 427 or 436. In any case, although the exact profile designations are unknown, they have been reproduced on the basis of numerical data tabulated on the original designs of the engine included in the manual as in [4]. As the official NACA designation of the profiles is not available, it has not been possible to take full advantage of the performance data from literature, however, having obtained some typical characteristics of the original 'family' from the section profiles, from numerical data, and from other texts (see in [9]), it was possible analyse about isolated profile performance and about the relative cascade for the parent profiles of the object of this investigation. The airfoil profile which is the object of this study (see Fig. 1) is thus that of the blades of stage 7 and 8 of the CF6-50 engine and it has been reconstructed, as previously mentioned, on the basis of the manufacturer's tables.

Figure 1: Test Airfoil Profile: Original And Worn Versions

The worn airfoil profile was reconstructed modifying the Leading Edge Roughness (LER) and the chord according to data that predict the surface wear for the blades according to the operating life of the engine, as well as through data supplied from those responsible for maintenance.

It is known, from the manufacturer's data, that erosion causes an increase in LER equal to 0.0002 inches every 1,000 flight hours, and a chord reduction of 0.003 inches every 1,000 flight hours. In our case we have assumed that the profile was extracted from an engine with 6,000 flight hours, corresponding to a time interval related to the aircraft engine's first service, as

reported by the engine maintenance staff. Having taken this flight time period into consideration is in line with the assumptions of other researchers that took 6,000-8,000 hours service as a time reference to quantify the effects of erosion, and actually for the CF6 engine (see in [14]).

Given the small size of the blades and the worn parts, in order to highlight the various effects experienced, the models were magnified so that the blades tested on the Water Table had a chord on a scale of 8.682:1; in choosing the size of the profile, we tried to avoid interference phenomena with the walls of the section tested. Thus instead of the original profile of 24.95cm, the following sizes were used for the profiles: worn 24.55 cm, restored by grinding (SWECO) 24.45 cm and restored in similitude 24.3 cm. The efflux around the profile was examined at a Mach number equal to around 0.86, and a Reynolds number between 8.16×10^6 and 8.33×10^6 . These values are those resulting from a flight quota of 10,668 m, with a rotation speed at the tip of the blade $u = 360$ m/s and a relative speed $w_1 = 387.96$ m/s calculated at around $\frac{3}{4}$ of the blade spanwise and a degree of reaction equal to 0.668 and with an inlet temperature at the 8° stage $T = 500$ K. The Reynolds number range explored is of the same order of magnitude, even if inferior, as that referred to by [6] and an agreement was found with the relationship referred to by them and attributed to Hudson dated 1991, according to which the efficiency ratio is proportional to $(Re)^{0.038}$.

3. Analysis of the flow of foulant or abrasive particles ingested by the engine

As mentioned also in [10], a considerable reduction in the performance and operating life of GT for stationary and aeronautical applications is caused by erosion of the blade surfaces of the compressor, due to solid particle ingestion and fouling caused by the depositing of various materials ingested with fouling characteristics and/or by adsorption properties towards the metal surfaces. The question has been described in [10] in the following terms:

I) description of the inlet flow with analysis of the mass and volume content of the abrasive and/or foulant particles and their characteristics;

II) description of the abrasive phenomenon by applying the model of impact;

III) correlation between the time of operation and the change in blade geometry;

IV) reproduction of the operating conditions in similitude to reproduce the flow of abrasive and foulant particles;

V) comparison of the trajectories of the particles around the profiles and through the cascade to verify the validity of the model of impact and abrasion. Through the studies of published authors ([10], [18] and [3]) it was possible to identify models to characterize the inlet flow and the characteristics of the particle-profile interaction, the result of which consists in the change of the blade surfaces, previously mentioned on various occasions. The description of the characteristics

of these airborne particles, which give rise to a mixed liquid/solid flow carried in the air, had been shown in a previous paper [10] as in the following equations. The first hypothesis (see in [18]) is represented by a ‘continuum having a local mass density per unit of volume’. Consequently, we have the approach suggested by [10] in which $\mathbf{X}$ is position, $\mathbf{f}(\mathbf{x}, \mathbf{v}, \mathbf{t})$ is the statistic distribution about particles, with $\mathbf{x}$ the spatial coordinate, $\mathbf{v}$ the efflux velocity and $\mathbf{t}$ the time, with $\mathbf{f}(\mathbf{x}, \mathbf{v}; \mathbf{t})\delta\mathbf{x}\delta\mathbf{v}$ as the number of particles which at the time $\mathbf{t}$ have a position (coordinate) between $\mathbf{x}$ and $\mathbf{x}+\delta\mathbf{x}$ and whose velocity falls between $\mathbf{v}+\delta\mathbf{v}$. If $(\delta\mathbf{x}, \delta\mathbf{v}) \rightarrow 0$ the volume of the phase contains a sufficient number of particles to enable the statistic distribution to be used. To improve the description it is useful to introduce the “mean radius” $\langle r_0 \rangle$ and its variance $\langle \Delta r_0^2 \rangle$ with respect to the population of particles and a function of integral distribution in a random but finite volume, $V_0[\mathbf{x}_0(\mathbf{t})]$, around a physical position $\mathbf{x}_0$, which can thus be written:

$$\Phi_0(r, \mathbf{x}_0; \mathbf{t}) = \int_{V_0} f(r, \mathbf{x}; \mathbf{t}) dV_0(\mathbf{x}) \quad (1)$$

Where the integral function Φ_0 represents the number of particles which at the time $\mathbf{t}$ are within volume V_0 around $\mathbf{x}_0$ and whose average radius is included in the elementary interval δr . Each dimension or average property (Ψ) related to the particles can therefore be expressed as:

$$\Psi_0(r, \mathbf{x}_0; \mathbf{t}) = \frac{1}{\Phi_0(r, \mathbf{x}_0; \mathbf{t})} \int_{V_0} f(r, \mathbf{x}; \mathbf{t}) \Psi(r, \mathbf{x}; \mathbf{t}) dV_0(\mathbf{x}) \quad (2)$$

Therefore, for example, the “average radius” of the particles which participate in the interaction can be written:

$$\langle r_0 \rangle(\mathbf{x}_0; \mathbf{t}) = \frac{1}{N_0(\mathbf{x}_0; \mathbf{t})} \int_0^\infty r \Phi_0(r, \mathbf{x}_0; \mathbf{t}) dr \quad (3)$$

$$\langle \Delta r_0^2 \rangle(\mathbf{x}_0; \mathbf{t}) = \frac{1}{N_0(\mathbf{x}_0; \mathbf{t})} \int_0^\infty [r - \langle r_0 \rangle(\mathbf{x}_0; \mathbf{t})]^2 \Phi_0(r, \mathbf{x}_0; \mathbf{t}) dr \quad (4)$$

where N_0 is the number of particles in the chosen volume and $\mathbf{u}_0$ is the velocity of the particles around $\mathbf{x}_0$ which are simply transported by the fluid which carries them. Since no force has been introduced, there is no reason to maintain that a differential distribution of the velocity of the fouling or abrasive particles exists. The second point to be examined is the characterization of fouling and abrasion. With regards to fouling and abrasion, as shown in [10] and [3], we can apply the following model of impact solid airborne particles/surface:

$$D_{eli} = \int_{el} \sigma_{ij} \epsilon_{ij} / (E_{fr} S_{el}) dV_{el} \quad (5)$$

where ϵ_{ij} and σ_{ij} represent the tensor of deformation and the tensor of stress respectively, while E_{fr} is the fracture energy of the material (of the blades for example) and S_{el} the surface of impact. Note that the fracture energy, V_{el} being the volume of the single element subjected to impact, is expressed:

$$E_{fr} = \int_{V_{el}} \sigma_{ij} \varepsilon_{ij} dV_{el} \quad (6)$$

From this formula the rate of erosion can be deduced, which, with M_p being the mass of the particles and $n_p=N_0$ being the number of particles with erosive characteristics, is equal to:

$$E_{eros_rate} = \rho_t \left(\frac{\sum D_{eli} m_{eli}}{n_p M_p} \right) \quad (7)$$

where m_{eli} is, obviously, the mass of the single element of the blade cascade subject to impact with the flow of abrasive particles. In (7) ρ_t represents the density of the material which forms the target of the impact. The impact has been outlined in Fig. 2.

Figure 2: Diagram of the Interaction of the Particle-Blade Cascade Impact as Proposed by [3]

On the basis of the damage function and the data provided by the maintenance staff of the CF6 engine, we can deduce two relationships which empirically explain the amount of geometry variation which is a consequence of the abrasion according to the outlined diagram of impact:

$$\Delta_{(-)} c = K a T \text{ (mm/flight hours)} \quad (8)$$

$$\Delta_{(+)} (LER) = H b T \text{ (mm/flight hours)} \quad (9)$$

which represent the decrease in chord length (c) and the increase in the radius at the L.E. (LER) respectively. The coefficients a , b , K and H are derived from experience until they can be modelled from similitude analysis. Coefficients “ a ” and “ b ” especially show the rate of change that is a consequence of wear in non-aggressive environments, while coefficients “ K ” and “ H ” take into account the environment operating conditions and show how normal wear can worsen because of the effects of the characteristics of aggression of the particles of impact.

In the case which is the object of this present study, the data recorded below in Table 3 was obtained on the basis of statistics compiled by staff in charge of maintenance.

Table 3.

Coefficient	Value	Unit
a	$7.62 \cdot 10 \text{ exp-5}$	mm/flight hours
b	$5.08 \cdot 10 \text{ exp-6}$	mm/flight hours
K	1 – 1.5	nondimensional
H	1 – 1.15	nondimensionale

4. Test Equipment

The profiles, which were reproduced in similitude and on a larger scale, were tested using Lamb's Hydraulic Analogy on the Water Table Test Bench at the 'Dipartimento di Ingegneria Meccanica ed Aerospaziale' at the University of Rome. As known, the rules shown in Table 4 below are valid for the analogy. As known, in the Hydraulic Analogy, the Reynolds number (Re) cannot be reproduced in the same way as the Mach number, that is equal to the Froude number. However, on the basis of an important contribution by [17] it has been shown through experiments that the efflux in the air and on the Water Table behave in the same way even if the Re numbers are different.

Table 4: Characteristic Parameters of Lamb's Analogy

Gas Flow	Water Flow
Pressure Wave Speed: $c=(KRT)^{0.5}$	Gravity Long Wave Speed $a=(gh)^{0.5}$
Mach Number: $Ma=u/c$	Froude Number: $Fr=u/a=u/(gh)^{0.5}$
Density Ratio: ρ/ρ_0	Water Heights Ratio: h/h_0
Pressure Coefficient Ratio: p/p_0	Water Heights Square Ratio: $(h/h_0)^2$
Temperature Ratio: T/T_0	Water Heights Ratio: h/h_0

Figure 3: Diagram Showing The Evaluation Of Error Using The Analogy.

The tests, as established by [11], were carried out within the Re range in which the Strouhal number is kept independent from Re's variation, with the undoubted benefit of being able to take advantage of the lengthening of non-stationary phenomena made possible by the Analogy. In Lamb's Analogy, the exponent k of the adiabatic process is equal to 2 and not to 1.4, thus, by approximating the efflux in the air with that in the "hydraulic gas" an error is introduced which increases with the Ma number. This error is between 4.5% for Ma=Fr=0.4 and 13.3% approximately, where Ma=Fr=0.8 as shown in Fig. 3. Specific corrections have been taken into account such that the chord, for some attack angles, becomes of the same order of magnitude as the flow free section. The above mentioned corrections are provided (in terms of the lift coefficient c_L), with reference to the chord c and length of the test section h, from:

$$\Delta c_L = c_L \cdot \left[-\frac{\pi^2}{48} \cdot \left(\frac{c}{h} \right)^2 + \frac{7 \cdot \pi^4}{3072} \cdot \left(\frac{c}{h} \right)^4 \right] \quad (10)$$

5. Tests Carried Out

Essentially two types of tests were carried out: those on the isolated profile and those on the profile cascade. In both cases tests were then carried out both on profiles in the original conditions and with varied geometry and then, finally, with geometry restored through grinding and in similitude conditions. Test outlines are shown in Figures 4 and 5, while the following typical equation was used to calculate the lift coefficient:

$$c_L = \frac{\cos \alpha}{2 \cdot Fr^2 \cdot h_\infty^2 \cdot l} \cdot \sum_i \left[(h_i^2 + h_{i+1}^2)_{\text{sup}} - (h_i^2 + h_{i+1}^2)_{\text{inf}} \right] \cdot X_i \quad (11)$$

where l is the chord length, α the angle of incidence, h the height at the sides of the profile and X_i the points of measurement along the chord.

Figure 4: Isolated Profile

Figure 5: Cascade

Table 5 shows the test results from the isolated profile in various conditions at corresponding various values of Ma=Fr, respectively, at various selected operating conditions.

As seen from the data in Table 5, at cruising speed, when passing from the original profile to the worn one there is a reduction of 6.30% in the lift coefficient. The surface grinding enables a recovery of only 1%, while with the restoration in similitude there is, on the contrary, an increase

in the lift coefficient in comparison with the original conditions. This paradox is attributed to the fact that with the restoration in similitude there is a noticeable reduction of the chord compared to the original. Concerning the tests on the cascade, after introducing Weinig's K coefficient:

$$\frac{C_{LS}}{C_{Lis}} = K \quad (12)$$

with its well-known parameters, the results in Table 6 lead to the conclusion that the average value of K is equal to 0.72 compared to 0.613 which would be obtained from Weinig's diagrams.

Table 5: Airfoil Test Results (Lift Coefficients) (Fr=Ma in the Analogy)

Alpha	Fr=0.6	Fr=0.7	Fr=0.8	Fr=0.86	Surface Condition
0	2.363	1.944	1.614	1.476	Original
0	2.164	1.573	1.402	1.383	Worn
0	2.147	1.663	1.447	1.397	Grinded
0	2.200	1.758	1.504	1.529	Restored in Similitude
N.B.: When Ma=Fr there are different engine rpm in different flight conditions					
	Ma=0.6	low rpm			
	Ma=0.7	low rpm			
	Ma=0.8	middle rpm			
	Ma=0.86	cruise rpm			

The fact that the lift coefficient of the profiles in cascade is lower than that of the isolated profile is due to the fact that the angle of pitch is around 43°, less therefore than the limit set at 45°, the value at which both the isolated profile and the cascade profile have the same lift. The stagger angle was about 16.5°-18.5°, while t/c ratio is about 0.79-0.55 in various tests.

Finally, the result obtained from the incident particle trajectories is shown in Table 6. The incident particles were visualized using an insemination of tobacco particles in the upstream water current.

Table 6: Test Results From The Cascade Compared To Those From The Isolated Profile (Lift Coefficients) (Fr=Ma In The Analogy)

Cascade alpha=0	Fr=0.6	Fr=0.7
original	1.715	1.397
worn	1.538	1.127
Isolated profile alpha=0		
original	2.363	1.944
worn	2.164	1.573

The trajectories shown in Fig. 6 appear to agree with those recorded by other authors as do the results from the aforementioned scientific literature. Unfortunately the only shortcoming is due

to the fact that it has not yet been possible to carry out the test with the tracer particles properly scaled down for the experiment in similitude conditions.

Figure 6: Image of the Incident Particle Trajectories

However, it is believed that if another type of tracer is used (of the type used in the Particle Image Velocimetry technique) or if the tobacco is refined further, it should be possible to remedy this problem. Although the scaling problem exists, the results are not only qualitative as in comparison with data in [4], [10] and [1].

6. Analysis of Trajectories of Incident Particles

FIGURE 7

FIGURE 8

In the Figs. 7 and 8 the specific fields of motion around a blade are shown by the false colours technique to underline the impacting flows, the different wind speeds and the interactions between impacting particles (with their trajectories) and the blade.

The pictures have been realised with a false colours photographic technique and show the trajectories of foulant particles. In Figs 10 and 11 the impact of particles with blade surface is explained in all the possible kinds.

Figure 10

The conditions exposed in previous Figs. 8, 9, 10 and 11, as reported by [19], may be realised in situations as in Fig. 12 where is shown an Harrier in arrival phase on the deck of an aircraft carrier.

Figure 11

Figure 12

7. Conclusions

This research work began with an in-depth analysis of the problem of L.E. erosion on the airfoil profiles of the compressor under examination. In fact a rigorous study of the erosion mechanism caused by an impact of a particle flow with the airfoil profile surface was carried out. All the parameters characteristic of efflux were tested in similitude conditions on the Water Table Test Bench except for the physical dimensions of the particles used in the tests. They were

not included in this current experiment because of the above mentioned problems with the water flow release and correct representation of the particle-blade interaction. Apart from this, the mathematical representation of the model of interaction was reproduced on the Water Table and the experimental determination of the lift coefficients was carried out using analytical reports derived from Lamb's Theory with modifications suggested by extensive experience in the study of efflux on the Water Table. This was also confirmed by numerical studies and the large scientific literature cited. The rigorous mathematical formulation of the problem examined has facilitated a more detailed analysis of the results obtained, as the prediction of impact was verified in laboratory conditions making it possible to reproduce a close approximation of the interactions which actually occur. The results obtained regarding the decrease in aerodynamic performance of the profiles due to erosion, in the light of the mathematical framework of the problem, confirm the statistics taken from scientific literature and from the maintenance reports on the engines. The mathematical framework of the type of interaction and the results of the experiment, far from being merely descriptive (they were in fact obtained and not only as order of magnitude of the performance), enabled us to obtain guidance on the improvement of maintenance techniques aimed at maintaining high aerodynamic performance of the cascade and of the single airfoil profiles. The conditions of fouling and erosion may be realised as during the arrival phase on the deck of an aircraft carrier, as in the case of an HARRIER. The corresponding action of particles on blade surface have been analysed. Work carried out has shown how restoring in similitude conditions is better than with a grinding machine but, apart from being more expensive, it can also be used fewer times because of the obvious reduction in the length of the profiles' chords. Therefore the restoration is only applicable once before replacing the worn blade, while the grinder can be used three or four times, giving the advantage of a longer life for the engine parts. Once again the usefulness of the Water Table has been shown for easily obtaining good cost effective results. In the near future, plans have been made to verify the results obtained testing the profiles in wind tunnels, while extending and improving the tests by using suitable tracers to increase our knowledge of the interaction between the flow of particles and the surface of the blade. First and foremost however, attempts will be made to improve the modelling of the particles used as tracers by scaling them down to the proper size.

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