AERODYNAMICS OF FEATHERS

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Summary

Feathers are fully-fledged aerodynamic systems. The purpose of this article is to present some aerodynamic properties of the flight feather. Therefore, lift and drag were measured at variable angle of incidence of flow for two flight feathers of a common wood pigeon (*Columba Palumbus*) and a distinct experiment was conducted to verify the dependence of lift on velocity. For the model resulting from the experimental part, the approach was the exclusion of the possible deformation of the feather that resulted in an experimental constant dependence of drag on velocity. The Reynolds number Re used in the simulation was $Re = 40000$ which corresponds to a likely Reynolds number for bird flight. The main model was based on the thin airfoil theory and a Python program was compiled to calculate flow maps. Some observations were made on the pitching moment despite the lack of measurements, but were verified theoretically and with the simulation. These observations suggest that the thin airfoil theory is applicable on a feather despite the deformation process during flight. The flow maps obtained theoretically were similar to those from the simulation. It seems that the software used for the simulation uses thin airfoil theory to model the flow around the airfoil. That confirms the choice of our theoretical model. Feather study may contribute to improving biomimicry.

Introduction

Humans have always wanted to fly like birds. Engineering achieved airships, helicopters, planes... However the latter are barely imitations of bird's wings. The common approach is to study the wing independently from the bird and how the morphology of the wing influences the quality of the flight. Even if the wing contributes the most to the aerodynamics of flight, the bird also flies thanks to its feathers. The feather constitutes indeed a great asset in the improvement of lift and in the reduction of drag therefore efforts for the bird. Moreover the feather itself may be extremely solid and simultaneously flexible which allows it to curve depending on the flow around.

During previous studies of bird's flight like Van Den Berg and Rayner's (1995) and Usherwood's (2008), experiments were conducted on complete wings and the aerodynamic forces were studied at the wing scale, not at the feather scale. In his thesis (2006), H. Beaufrère points out the influence of some feather configurations for both lift and drag in the flight of gliders, swift (*Apus apus*) and great skua (*Stercorarius skua*). However the feather had never really been studied as an independent aerodynamic system. Only air transmissivity was measured for several feathers of a kestrel (*Falco tinnunculus*) in a publication by Muller and Pattone (1998).

The purpose of this study was to determine the aerodynamic properties of flight feathers and to establish a mathematical model of the flow around the feather. This model may help in the development of future plane wings and should unable further comprehension of bird flight. The experiments conducted may also help with identifying precisely the position of a feather on the wing without knowing the origin of the feather, only considering the helix described by the feather when it falls.

A short introduction to thin airfoil theory

In this paper, the main idea of the theoretical part is based on the thin airfoil theory. It corresponds to the analog in fluid mechanics of the method of image charges in electrostatics.

The airfoil is indeed replaced by a distribution of vorticity γ along the chord of the airfoil.

$$\gamma(\theta) = A_0 \frac{1 + cos(\theta)}{sin(\theta)} + \sum_{i=1}^{+\infty} A_n sin(2n\pi\theta)$$

The A_n are the Glauert coefficients given by:

$$A_0 = \alpha - \frac{1}{\pi} \int_0^{\pi} \frac{dz}{dx} (\frac{1 - cos(\theta)}{2}) \, \mathrm{d}\theta$$

$$\forall n \in \mathbb{N}^*, A_n = \frac{2}{\pi} \int_0^{\pi} \frac{dz}{dx} (\frac{1 - cos(\theta)}{2}) \, \mathrm{d}\theta, n \geq 1$$

With this expression of γ, the velocity field can be calculated using the following formulae based on the Kutta-Joukowski conditions:

$$v_x(x, z) = \frac{1}{2\pi} \int_0^{\pi} \gamma(\theta) \, \frac{z}{(x - \frac{1-cos(\theta)}{2})^2 + z^2} sin(\theta) \, \mathrm{d}\theta$$

$$v_z(x, z) = -\frac{1}{2\pi} \int_0^{\pi} \gamma(\theta) \, \frac{x - \frac{1-cos(\theta)}{2}}{(x - \frac{1-cos(\theta)}{2})^2 + z^2} sin(\theta) \, \mathrm{d}\theta$$

with v_x is the flow velocity on the x axis and v_z is the one on the z axis.

Materials and Methods

For the determination of the aerodynamic characteristics of the feather, two primaries (*remiges primariae* RP) of a common wood pigeon (*Columba Palumbus*) were used, the third and the ninth primaries (RP3 and RP9 in the nomenclature of feathers). Both of them come from my personal collection and were desinfected before use. All experiments were conducted at room temperature (about 25^o) so that the viscosity of air could be approximated with $\nu = 1.568\ 10^{-5}\ m^2 s^{-1}$ (see Python script for use of the approximation).

To measure lift and drag, air was blown at the feather perpendicular to the rachis in order to recreate the flight conditions, at least for the feather RP3. The prop of the feathers was made to enable both variation and measurement of the angle of incidence of the flow.

Lift was measured using a weighing scale and the equation used for the conversion weight/lift is the following: $L = -\Delta m_{measured}\ g$ with L the lift and g the constant of gravitation ($g = 9.81\ ms^{-2}$). On the other hand, to obtain drag values, I used a dynamometer placed above the system and linked with the feather via a pulley (Fig 1).

These experiments were made for 2 different flow velocities (measured with an anemometer) when the lift and drag were both measured. A previous verification of the lift dependency in velocity $L \propto v^2$ was carried out with RP9.

After the experimental section, a computing simulation was conducted using the software JavaFoil® to visualize the flow cartography around the feather. It also permitted confirmation of some experimental results, like the form of the lift/drag curve.

Finally, based on thin airfoil theory, I computed a Python® program that calculates a flow map given an airfoil. The airfoil used to model RP9 is a third-degree polynomial function (Fig 2).

Air velocity (ms^{-1})	Lift (N)
3.0	$3.92\ 10^{-3}$
3.4	$7.85\ 10^{-3}$
4.0	$1.18\ 10^{-2}$
4.5	$1.77\ 10^{-2}$
4.8	$2.26\ 10^{-2}$
5.25	$2.84\ 10^{-2}$
5.5	$3.24\ 10^{-2}$
5.85	$3.70\ 10^{-2}$
6.0	$4.12\ 10^{-2}$
6.5	$4.91\ 10^{-2}$

Table 1: Lift: function of velocity

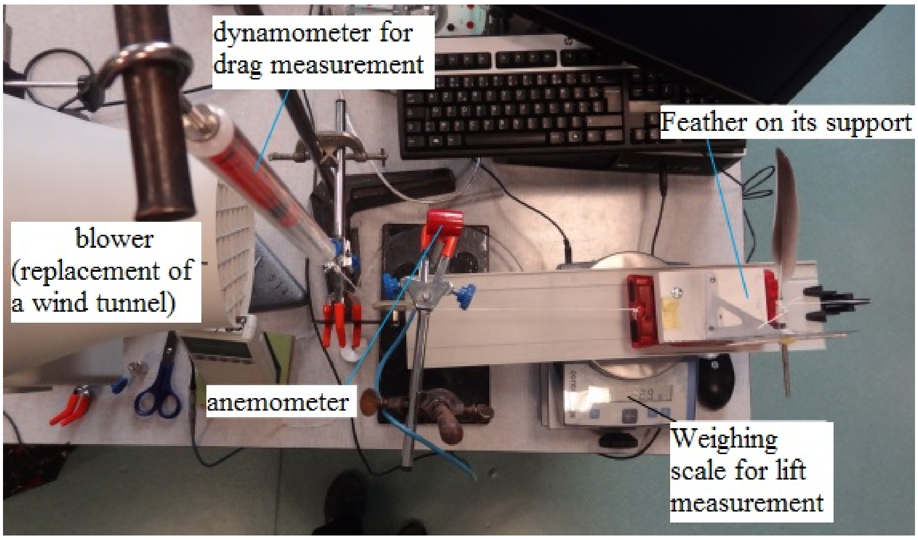

Figure 1: Experimental set-up

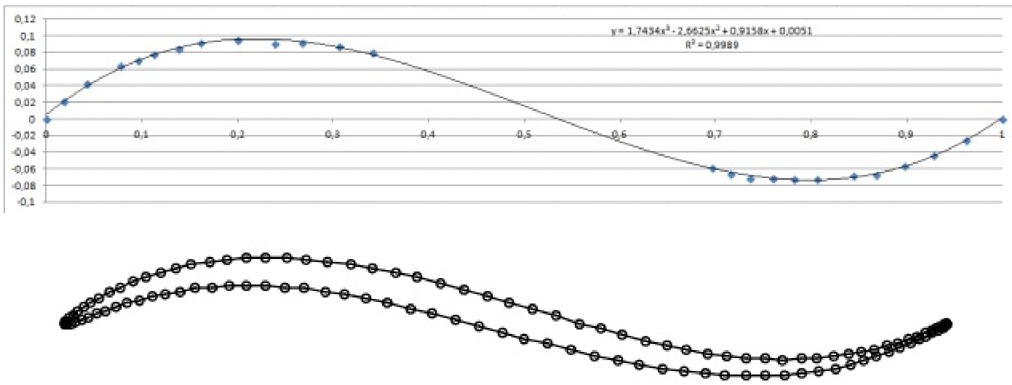

Figure 2: Upper: airfoil used for the theoretical calculation / Lower: airfoil used in the simulation on JavaFoil®

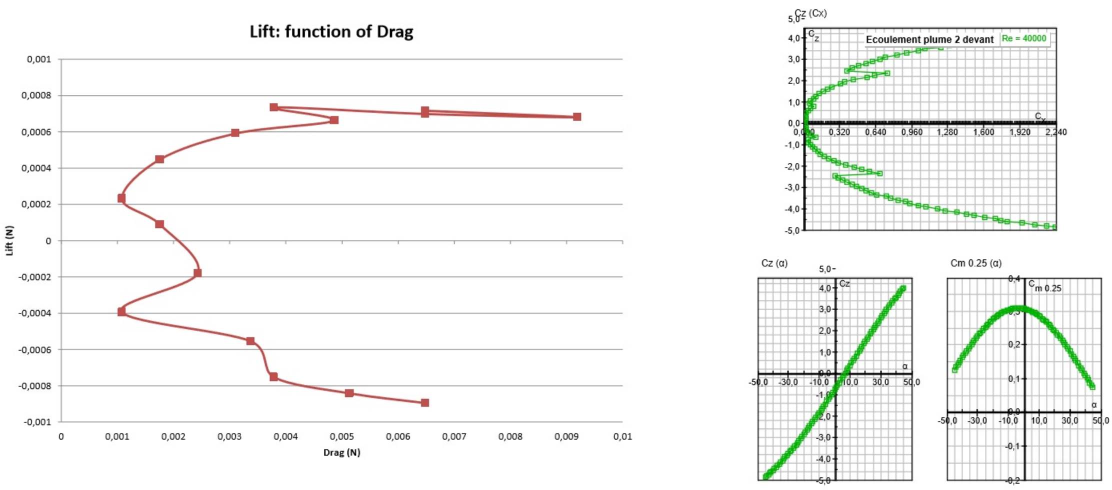

Figure 3: On the left: lift function of drag / On the right: at the top: Lift function of drag, at the bottom left: lift function of angle of incidence and at the bottom right: pitching moment function of angle of incidence

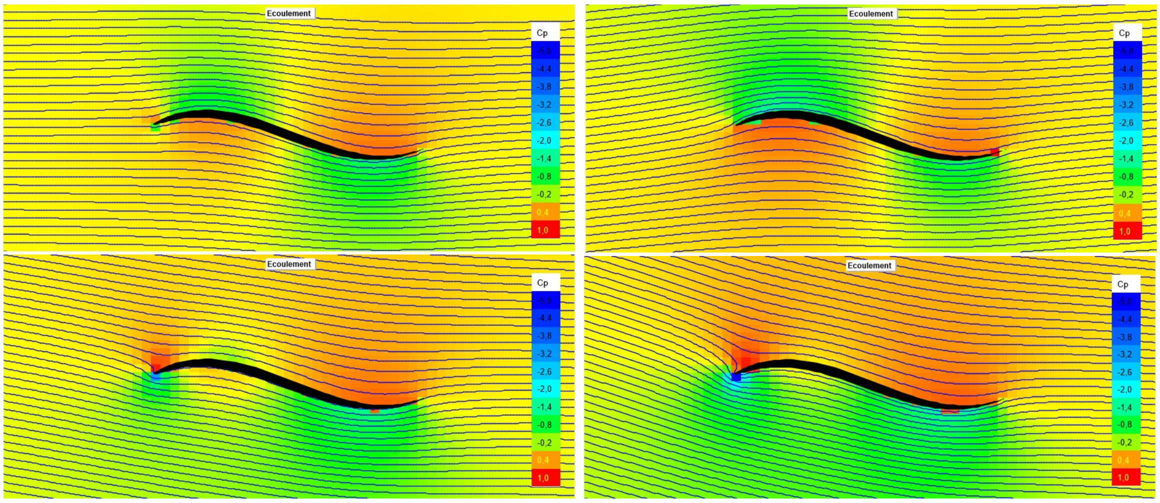

Figure 4: Flow maps for angle of incidence (0^o top left, 4^o top right, -6^o bottom left, -10^o bottom right

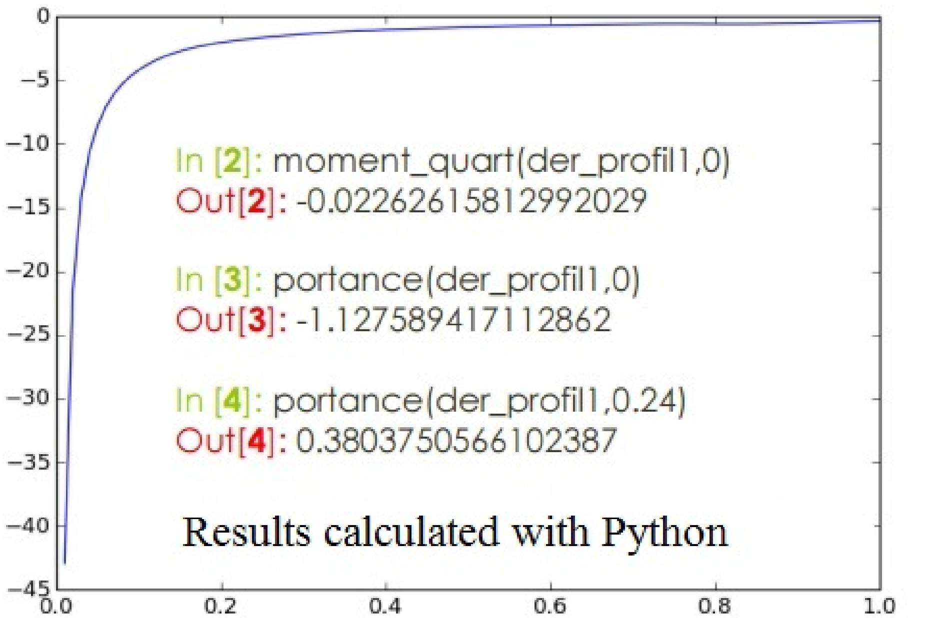

Figure 5: Density of vorticity and calculation of pitching moment and lift associated with the modelled airfoil of RP9

Results

Lift at set angle of incidence

The results of lift measurements for RP9 for different air velocities are shown in Tab 1. The data permit the verification of the evolution law: $L = \frac{1}{2}\rho S v^2 C_L$ with ρ the air density, S the surface of contact, v the air velocity and C_L the lift coefficient. Indeed a linear regression on the data brought up a coefficient of determination $R^2 = 0.997$. That law was also verified while changing the angle of incidence of the flow. The same experiment of the influence of the angle of incidence was indeed conducted for 4 different air velocities.

However if the lift seems to evolve according to the theory, the drag doesn't show the same properties.

Drag and Lift at set air velocity

The results for the lift, function of drag (and angle of incidence), of RP3 are shown in Fig 2. The simulation shows the same evolution (Fig 2).

The angle of null lift has also been measured and calculated but since the feather changed position during the experiment, the result was not conclusive. Moreover, because of the deformation, the chord of the feather cannot be defined precisely during the experiment.

Furthermore, what could not be measured during the laboratory experiments but could be seen, is the pitching moment of the feather when the flow has an angle of incidence that is not zero. The simulation however calculates the pitching moment at the quart-chord point, that corresponds to the rachis.

Flow maps

The software JavaFoil® was used to simulate flow around the feather, which should have been possible in laboratory using optical methods or particle tracer methods. On the Fig4, four flow maps were calculated for different angles of incidence.

Theoretical results

The Python script is available at the end of the paper. The curve representing the feather calculated on the basis of a feather photograph is $z(x) = 1.7434x^3 + 2.6625x^2 + 0.9158x + 0.0051$. The display of the flow maps is to be done again because the computer couldn't achieve the calculation. However, the distribution of vorticity was calculated and the graph is shown in Fig 5.

Discussion

Aerodynamics of the feather

The feather showed no sign of stall during the experiment, be it RP3 or RP9. This may be explained by the deformation of the vane of the feather. Indeed, the feather is extremely flexible on its inner vane [1]. That brings a additional lift contribution as it creates a vortex flow at the feather surface.

As previously mentioned, the non null pitching moment was observed during the experiment despite the solid friction at the joint of the support. It was confirmed by theory but it could also be explained by the structure of the feather. With its double-curvature, pressure is not homogeneous on the upper (lower) surface of the feather. Therefore, it creates a difference of lift between the outer and inner vanes, which leads to a pitching moment.

The results also tend to show that the orientation of the feather which maximizes the lift and minimizes the drag corresponds to the orientation of the feather on the wing.

Limits to the model

The model seems to reflect reality to a certain extent. However, due to repeated approximations, the model has been considerably simplified, so that parameters like Reynolds number, surface of contact feather/air, etc. do not appear in our model. However, these parameters should be key to better understand the boundary layer around the feather.

Furthermore, because of its biological nature, a feather is really difficult to model. Its structure and precise composition are unique to each feather and unless by doing complete study of its organisation, some experiment parameters will remain unknown.

Moreover, the present program takes too much time to execute, which could be reduced using parallel computing to accelerate the calculations.

Future work

In the future, the videos taken during the experiment of the fall of different feathers, will be analyzed, in order to verify the last hypothesis concerning the best orientation of the feather.

Further investigation will also be done to generalize this work to other feathers from the common wood pigeon and other species.

Bibliography

- Articles from *The Journal of Experimental Biology*:
  - *The aerodynamics of revolving wings II. Propeller force coefficients from mayfly to quail*, James R. Usherwood and Charles P. Ellington, 2002
  - *Dynamic pressure maps for wings and tails of pigeons in slow, flapping flight, and their energetic implications*, James R. Usherwood, Tyson L. Hedrick, Craig P. McGowan and Andrew A. Biewener, 2004
  - *Air transmissivity of feathers*, Werner Müller and Giannino Patone, 1998
  - *The aerodynamics of avian take-off from direct pressure measurements in Canada geese (Branta canadensis)*, James R. Usherwood, Tyson L. Hedrick and Andrew A. Biewener, 2004
  - *The influence of wing–wake interactions on the production of aerodynamic forces in flapping flight*, James M. Birch and Michael H. Dickinson, 2003
- *La plume et le vol*, Hugues Beaufrère
- *The aerodynamic forces and pressure distribution of a revolving pigeon wing*, James R. Usherwood, 2008

Annex

```
from numpy import *
import scipy.integrate as si
import matplotlib.pyplot as mp

def profil1(x):
    return 1.7434*x**3+2.6625*x**2+0.9158*x+0.0051

def der_profil1(x):
    return 5.2302*x**2-5.3250*x+0.9158

def cos_part(x,n):
    return cos(2*pi*n*x)

def sin_part(x,n):
    return sin(2*pi*n*x)

def coeff_fourier(f,n,a):
    def cosf(x):
        return cos_part(x,n)*f((1-cos(x))/2)
    if n==0:
        return a-1/pi*(si.quad(cosf,0,pi))[0]
    return 2/pi*(si.quad(cosf,0,pi))[0]

def approximation_of_fourier(f,n,a):
    return [coeff_fourier(f,k,a) for k in range(n+1)]

def fourier(f,n,x,a):
    s=0
    l=approximation_of_fourier(f,n,a)
    for i in range(n+1):
        s+=cos_part(x,i)*l[i]
    return s

def vortices(f,n,x,a):
    l=approximation_of_fourier(f,n,a)
    s=l[0]*(1+cos(x))/(sin(x))
```

```
    for i in range(1,n+1):
        s+=sin_part(x,i)*l[i]
    return s

def lift(f,a):
    return pi*(coeff_fourier(f,0,a)*2+coeff_fourier(f,1,a))

def moment_0(f,a):
    return -pi*(coeff_fourier(f,0,a)+coeff_fourier(f,1,a)-coeff_fourier(f,2,a)/2)/2

def moment_quarter(f,a):
    return -pi/4*(coeff_fourier(f,1,a)-coeff_fourier(f,2,a))

def gamma1(x,a):
    return vortices(der_profil1,5,x,a)

def velocity_z(f,x,z,a):
    def gamma(t):
        return vortices(f,20,t,a)*(x-(1-cos(t))/2)/(1+(x-(1-cos(t))/2)**2+z**2)*sin(t)
    return -1/(2*pi)*si.quad(gamma,0,pi)[0]

def velocity_x(f,x,z,a):
    def gamma(t):
        return vortices(f,20,t,a)*sin(t)*z/(1+(x-(1-cos(t))/2)**2+z**2)
    return 1/(2*pi)*si.quad(gamma,0,pi)[0]

def psi_gamma(x,z,a):
    def aux(t):
        return gamma1(t,a)*log(z**2+(x-(1-cos(t))/2)**2)*sin(t)
    return -1/(2*pi)*si.quad(aux,0,pi)[0]

def angle_null_lift(f):
    def var(x):
        return f(cos(x)-1)*sin(x)
    return -si.quad(var,0,1)[0]

def velocity_gamma(x,z,a):
    u=velocity_x(der_profil1,x,z,a)
    w=velocity_z(der_profil1,x,z,a)
    return (w,-u*der_profil1(x))

def flow_maps(v,n,a):
    z=[-0.01+i*0.005 for i in range(20)]
    x=[i*1/n for i in range(n+2)]
    for i in range(n+2):
        for j in range(20):
            p,q=x[i],z[j]
            u,w=velocity_gamma(p,q,a)
            mp.plot([x[i],x[i]+v*u],[z[j],z[j]+v*w])
    mp.show()

def lift_evolution(f):
    A=[(-90+i*5)/360*2*pi for i in range(49)]
    p=[lift(f,a) for a in A]
    mp.plot(A,p)
    mp.show()
```