Improving the modeling of the Fenestron – R.HUOT - Eurocopter

Master Thesis

Improving the modeling of the Fenestron® in the Eurocopter Simulation Tool

Rémy HUOT – Flight Mechanics department – remy.huot@eurocopter.com
Kungliga Tekniska Högskolan – SE – 100 44 Stockholm

Abstract - The main objective of this study carried on among the Flight Mechanics and Loads department of Eurocopter Marignane was to analyze the existing model of the Fenestron named “type 2” and make a separation of the thrust created by the propeller and the one created by the shroud around it. The physics had to be brought back in this model to avoid using tuning parameters. The validity and the reliability of the modeling were then checked with flight tests, wind tunnel and CFD results analysis.

Nomenclature

- Density of air
- Total pressure
- Total area of the fan
- Area of a ring
- Fan radius
- Radius of a blade element
- Width of ring
- Engine torque
- Rotor torque
- Rotation speed of the Fenestron
- Helicopter yaw angle
- Helicopter yaw rate

Introduction

The modeling has a growing importance among the design offices. Indeed, the numerical simulation strongly reduces the costs by avoiding some expensive wind tunnel and flight tests. Moreover, when the models are optimized, flight simulators can be developed to train the pilots.

The objective here was to improve the modeling of the Fenestron in the simulation tool HOST. The Fenestron, also called Fan-In-Fin is a shrouded tail rotor invented and patented by Eurocopter in 1968, mainly to enhance the safety.

Figure 1: A Fenestron seen from the diffuser side
Improving the modeling of the Fenestron – R.HUOT - Eurocopter

Besides the gain of safety, the Fenestron takes great benefits from its shroud to decrease the required power to deliver a given thrust. Indeed, at hover, the thrust is distributed equally between the propeller and the force of the shroud created by the low pressures on the lips of the collector (see Figure 3).

In forward flight, the performances decrease a lot. This is why a big rudder is placed on the top of the shroud: it counters the torque of the main rotor and relieves the Fenestron. In cruise, the power consumed by the latter is then around zero.

After a brief description of the simulation tool HOST, the first part of this paper focus on the previous modeling in order to highlight the problems and the possible ways of improvements. After some modifications done to bring back the physics in the modeling, comparisons with flight tests, wind tunnel and CFD analysis are made in order to see the reliability and the validity of the model.

For the sake of confidentiality, the Fenestrons on which the studies have been carried on will be called Fenestron 1 & 2 and no helicopter name will be mentioned in this paper.

Moreover, the values of the induced velocities $V_i$ at the propeller are removed on the figures and the axis of the polars $F_{fen} = \theta$ aren’t numbered.

Conventions

The helicopter frame of reference is defined as shown in Figure 2.

![Figure 2: Helicopter frame of reference](image)

It is important to notice that the rotation of the main rotor corresponds here to a French aircraft. For the German and American helicopters, the rotor rotates in the other way and the thrust of the Fenestron/Tail rotor is then along the $\hat{y}$ axis.

A Fenestron frame of reference, shown in Figure 4, has also been defined for the model Type 2. The same one will be used for the new modeling.

![Figure 4: Fenestron frame of reference](image)

It will particularly be noticed that when the flow goes from the collector to the diffuser, the thrust is oriented along $-\hat{y}$ in the helicopter frame of reference and along $-\hat{z}$ in the Fenestron frame of reference.

Furthermore, we talk about left lateral flight when the wind is on the side of the collector and right lateral flight when it is on the side of the diffuser (French helicopter conventions).
Improving the modeling of the Fenestron – R.HUOT - Eurocopter

Note: a positive blade pitch corresponds, at hover, to a flow from the collector to the diffuser.

HOST

HOST for Helicopter Overall Simulation Tool is the simulation tool used by Eurocopter for a various number of studies such as handling qualities, loads, automatic pilot definition and vibrations. This is a global code of the helicopter flight mechanics, in FORTRAN language, which enables the calculation of trim equilibrium, flight simulations and the dynamic analysis of the helicopter through a linearization around a trimmed position. For that, it uses geometrical and inertial data of every aircraft and aerodynamic coefficients delivered by wind tunnel tests. Considering the modeling of the Fenestron in this software, various models can be chosen by the users (Analytical, Type 2, Interpolated, Krämer). A description of these models is made in [4]. Their objective is to compute the thrust of the Fenestron knowing the pitch angle imposed by the pilot, the flight conditions (altitude, speed, sideslip…) and the geometrical data of the device (blades, shroud…).

Only the model type 2 will be highlighted in this paper, as it is the most widely used among the Eurocopter engineers.

The previous model [Type 2]

First model to represent the behavior of the Fenestron, this is an analytical model based on the following method: find a good modeling of the Fenestron in Hover, extend it to the forward flight and then introduce the sideslip and the lateral flight.

Principle & Hypothesis

The general principle of this modeling is to discretize the disc of the fan in different rings of the same area \( S_a \) and calculate the thrust contribution of each ring. Therefore, the model is more suited to account for the variation of twist along the blade span. The total thrust is then computed by adding the different elementary forces.

In the frame of this model, it will be assumed that the induced velocity of the fan is purely axial (along the rotation axis of the Fenestron). Thus there is no gyration of the flow downstream. This hypothesis is verified when using anti-swirl vanes. It will also be assumed that the induced velocity \( V_i \) is uniform on a ring. Finally, the Bernoulli’s equation will be used to compute the induced Velocity, so the flow is considered inviscid, irrotational and incompressible.

The thrust at hover

In this model developed by Alain Cler in 1987 [1], the thrust of the Fenestron isn’t calculated by computing separately the thrust of the fan and the thrust of the shroud. He actually applied the momentum theory on every ring of the propeller. For a mass flow rate \( q \).

\[
\text{Upstream: } qV_m^* = \vec{0} \text{ at hover} \quad (1)
\]

\[
\text{Downstream: } qV_o = |\rho V_i S_a| \cdot \frac{V^*}{\sigma_{\text{max}}} \quad (2)
\]

Thus the force of the ring on the fluid is

\[
q\vec{V}_o - q\vec{V}_m^* = q\vec{V}_o^* \quad (3)
\]

The force on a ring at hover is then

\[
\vec{F}_a = \rho S_a \left( -\frac{V_i^2}{\sigma_{\text{max}}} \right) \cdot \text{sign}(V_i) \quad (4)
\]
And the thrust of the Fenestron becomes

$$ F_{fen} = \sum_{rings} F_a' $$

(5)

Furthermore, in the case of the Fan-In-Fin, the contraction of the flow $\sigma_{max}$ is equal to 1 and not 0.5 like for a classical tail rotor.

However, the contribution of the shroud isn’t well taken into account in this formulation. This is why Alain Cler in [1] adapted the values of the contraction $\sigma_{max}$ and of the $C_{za}$ of the blades to match the polars given by the wind tunnel tests done in 1987. He takes

$$ \sigma_{max} = \begin{cases} 0.6 & \text{in the direction collector} \\ 0.3 & \text{in the direction diffuser} \end{cases} $$

$$ C_{za} = 0.0657 \text{deg}^{-1} \text{ instead of } 0.1 \text{ deg}^{-1} $$

### Induced Velocity

The value of the induced Velocity $V_i$ is necessary when computing the thrust [(4) and (5)]. To obtain it, Alain Cler used two different equations modeling the thrust of the fan only, one based on Bernoulli’s formula (6), one based on a local calculation (7), giving

$$ T_a = S_a (P_{t,upstream} - P_{t,downstream}) $$

$$ = \frac{1}{2} \rho S_a \left( V_\infty^2 - \frac{V_i^2}{\sigma^2} \right) \cdot \text{sign}(V_i) $$

(6)

$$ T_a = \frac{1}{2} \rho [V_i^2 + (\omega r)^2] $$

$$ \times cb \Delta r \left[ -C_{za} (\theta - \alpha) \cos \alpha \right] $$

(7)

The induced velocity is then computed by a Newton algorithm which finds the value of $V_i$ that equalizes the two equations above.

The equation (7) has a great importance in the modeling as it uses the blade pitch $\theta$, which is controlled by the pilot with the paddles.

The thrust at hover can then be computed.

### Forward Flight

Alain Cler wants to find a suitable formulation in the case of forward flight.

First, he modifies the momentum theory and adds a term to take into account the translation speed.

$$ F_a = q \cdot \tilde{V}_\infty - q \cdot \frac{V_i}{\sigma_{max}} $$

(8)

However, in the case of forward flight, the Fenestron thrust is around zero as the rudder compensates the torque created by the rotor. The scheme of the airflow is then totally different compared with the flow established at hover.

- **Figure 6**: airflow in the Fenestron in forward flight

When the translation speed is higher than the induced velocity, the Fenestron behaves like a wing with a suction and a transpiration side [see Figure 6]. The equation (8) is thereby no more valid. Indeed, it is unlikely that the Fenestron recovers the total pressure of the upstream airflow at the propeller and the notion of contraction is less obvious. That is why the Fenestron is modeled in this condition with the Prandtl theory for an elliptic wing as

$$ \tilde{F}_{wing} = -2 \rho S_a \left\| V_\infty \right\| k(\varepsilon) \tilde{V}_i $$

(9)

where $k(\varepsilon)$ is an attenuating coefficient that cancels the force when $\frac{\left\| V_i \right\|}{\left\| \tilde{V}_i \right\|} \gg 1$ (corresponds to hover or low translation speed):

$$ \begin{cases} 
  k(\varepsilon) = 1 - \varepsilon \frac{3}{2} & \text{pour } \varepsilon = \frac{\left\| V_i \right\|}{\left\| V_\infty \right\|} < 1/2 \\
  k(\varepsilon) = 0 & \text{pour } \varepsilon = \frac{\left\| V_i \right\|}{\left\| V_\infty \right\|} > 1/2
\end{cases} $$

(10)

This function comes from a numerical optimization made to match the wind tunnel tests results.

The contraction is also modified in this condition in the calculation of the induced
velocity (6) in order to cancel the thrust \( T_a \) of each ring of the fan so that

\[
\sigma = \sigma_{\text{max}} \tanh \left( \frac{\|V\|/\|V_\infty\|}{\sigma_{\text{max}} \sqrt{1 - \text{sgn}(V_i) \cdot \frac{T_a}{\frac{1}{2} \rho V_\infty^2 S_A}}} \right)
\]

(11)

To resume,
- At low speed (8) is predominant over (9)
- At high speed (9) is predominant over (8)

**Sideslip**

Alain Cler then considers a component \( W \) in the translation speed of the helicopter, which corresponds to sideslip conditions.

Taking it into account in the elliptic wing force, it gives

\[
\vec{F}_{\text{Wing}} = 2 \rho k \varepsilon S_A \sin(\xi) \|V\| \cos(\xi) \cdot \vec{V}_\infty - \vec{V}_i \|V_\infty\|
\]

(12)

with \( \xi = \frac{\pi}{2} - \beta \)

In the case of zero-sideslip, the pressure is the same on each side of the propeller, and this is why its thrust is cancelled in the calculation of the induced velocity with (11). However, it is no more true in sideslip conditions. Indeed, there are now a low pressure and a high pressure side and the thrust of the propeller and the thrust of the propeller can be modeled with the Lift formulae of a profile:

\[
T_a = \frac{1}{2} \rho V_\infty^2 S_A K \beta
\]

(13)

Where \( K=2.5 \) and is a coefficient considered as universal but who actually depends on the geometry of the shroud.

The contraction in the calculation of the induced velocity is then again modified in order to obtain a propeller thrust equal to (13).

In high sideslip conditions, a term \( g(\xi) \) is introduced in the formulation of the contraction to model a drop in thrust observed experimentally when the lateral wind is opposed to the induced velocity.

To summarize
- **Induced velocity calculation**

The induced velocity calculation is made using the equations (6) and (7) with,

\[
\tan \alpha = \frac{V_i}{\omega r}, \quad C_{za} = 0.0657
\]

\[
\sigma = \sigma_{\text{max}} \tanh \left( \frac{\|V\|/\|V_\infty\|}{\sigma_{\text{max}} \sqrt{1 - K \rho g(\xi) \text{sgn}(V_i)}} \right)
\]

(14)

\[
\begin{align*}
\sigma_{\text{max}} &= 0.6 \text{ in the direction collector } \rightarrow \text{ diff user} \\
\sigma_{\text{max}} &= 0.3 \text{ in the direction diff user } \rightarrow \text{ collector} \\
K &= 2.5 \\
\beta &= V_{\text{ax}}/\|V_\infty\| \text{ and } \xi = \frac{\pi}{2} - \beta
\end{align*}
\]

A Newton algorithm computes the induced velocity with the system of two equations given by (6) and (7).

- **Thrust calculation**

\[
F_a = \left\{ \begin{array}{l}
q V_{\text{ax}} [1 + k(\varepsilon) \sin(2\xi)] \\
q V_{\text{ax}} [1 + k(\varepsilon) \sin(2\xi)] - q \frac{V}{\sigma_{\text{max}}} - 2qk(\varepsilon) \sin(\xi) \frac{V}{\xi}
\end{array} \right.
\]

\[
F_{\text{fen}} = \sum_{\text{rings}} F_a
\]

(15)

See [1] for more details on the modeling “Type 2”.

Despite the lack of physical meaning for some parameters like the contraction or the slope of the \( C_\alpha - \alpha \) polar of the blade, and some other readjustments done to match the wind tunnel polars, this model gives goods results at hover or in forward flight with low sideslip. It is however further from the reality for high sideslips and for high pitch inputs.

The objectives of the new modeling are then numerous:
- The model must have physical meanings to be predictive without readjusting the parameters
The propeller and the rotor thrust must be calculated separately.

- The induced velocities must be coherent compared with the results given by CFD computations.
- It must work for every flight conditions (hover, forward flight, climb, descent)

The new modeling

Principle & Hypothesis

The idea behind this new modeling was to dissociate the thrust created by the propeller from the thrust created by the low pressure on the lips of the shroud. It was also asked to set back the contraction and the slope $C_{ca}$ to their physical values. For that the general structure of the model Type 2 has been conserved.

The hypothesis and the conventions used in this new model are identical to the one used for the previous model. That is to say:

- The induced velocity is purely axial and uniform on each ring
- The airflow is assumed inviscid, irrotational and incompressible in order to use the Bernoulli’s formula.

Induced Velocity

Firstly, it has been noticed that the term $V_i$ calculated in the model type 2 isn’t actually the induced velocity but the sum of the induced velocity and the velocity of the upstream airflow as shown in Figure 8.

**Case 1:** Hover ($V_\infty = 0$) or left lateral flight

**Case 2:** Right lateral flight with high values of wind (when the force created by the air on the rudder creates a torque greater than the torque created by the main rotor).

**Case 3:** Right lateral flight with low values of wind.

The equation (6) is obtained applying the Bernoulli’s formulae where $V_i$ is the sum of $V_m$ and the induced velocity.

This observation induces some problems in some flight conditions. Indeed, in the case 3, the induced velocity is still in the direction collector–diffuser and, since the sign of $V_\infty$ isn’t taken into account in the formulation, the thrust is identical to the thrust in the case 1. Thus, questions are raised about the validity of the model in this condition (case 3).

Christophe Castelin, in [4] also raised the problem: “This formulation doesn’t correctly consider lateral wind from Euler point of view”

A new formulation of the thrust of the propeller has been written in order to improve the calculation of the induced velocity. Now $V_i$ really represents the induced velocity.

Applying the Bernoulli’s formula, it gives:

$T_h = S_h (P_{upstream} - P_{downstream})$

$= \rho S_h \left( W^2 - \left( W + \frac{V_i}{\sigma} \right)^2 \right) \cdot \text{sign}(V_i)$  \hspace{1cm} (16)
One can notice that we obtain the same equation than Alain Cler (6) in the case of hover (W=0) or left lateral flight (W>0).

This new thrust formulation is integrated in the calculation of the induced velocity by a Newton algorithm.

Hence,

\[
T_a = \frac{1}{2} \rho \left( (\frac{VI}{\sigma})^2 + (\omega r)^2 \right) * C_b \Delta r [ -C_{2a}(\theta - \alpha) \cos \alpha ]
\]  

(18)

With, \( \tan \alpha = \frac{V_i + W}{\omega r} \)

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contribution of the CFD

The objective of this part is to analyze the induced velocities values in the Fenestron 1 at the propeller. To do it, a comparison has been made between the results given by HOST and the results given by the CFD using the software ELSA, developed by ONERA.

First, the analysis has been done by discretizing the rotor disc in 5 rings and for different values of the blade pitch.

It can be noticed in the Figure 9 that the induced velocities values given by HOST with the model type 2 are far from the values given by the CFD. The fact that some parameters have been readjusted is the reason of it. With the new model and the new calculation of the induced velocities, the results are better as shown in Figure 10.

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contribution of the CFD

The objective of this part is to analyze the induced velocities values in the Fenestron 1 at the propeller. To do it, a comparison has been made between the results given by HOST and the results given by the CFD using the software ELSA, developed by ONERA.

First, the analysis has been done by discretizing the rotor disc in 5 rings and for different values of the blade pitch.

It can be noticed in the Figure 9 that the induced velocities values given by HOST with the model type 2 are far from the values given by the CFD. The fact that some parameters have been readjusted is the reason of it. With the new model and the new calculation of the induced velocities, the results are better as shown in Figure 10.

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contribution of the CFD

The objective of this part is to analyze the induced velocities values in the Fenestron 1 at the propeller. To do it, a comparison has been made between the results given by HOST and the results given by the CFD using the software ELSA, developed by ONERA.

First, the analysis has been done by discretizing the rotor disc in 5 rings and for different values of the blade pitch.

It can be noticed in the Figure 9 that the induced velocities values given by HOST with the model type 2 are far from the values given by the CFD. The fact that some parameters have been readjusted is the reason of it. With the new model and the new calculation of the induced velocities, the results are better as shown in Figure 10.

The contraction \( \sigma \) and the slope \( C_{2a} \) are also set back to their physical values (1 and 0.1 deg⁻¹).

The contribution of the CFD

The objective of this part is to analyze the induced velocities values in the Fenestron 1 at the propeller. To do it, a comparison has been made between the results given by HOST and the results given by the CFD using the software ELSA, developed by ONERA.

First, the analysis has been done by discretizing the rotor disc in 5 rings and for different values of the blade pitch.

It can be noticed in the Figure 9 that the induced velocities values given by HOST with the model type 2 are far from the values given by the CFD. The fact that some parameters have been readjusted is the reason of it. With the new model and the new calculation of the induced velocities, the results are better as shown in Figure 10.


\[ \Delta V_{i5}(V_i, W) = \text{fct}(V_i) + \Delta V_{i5}(V_i, W) \text{ for the ring 5} \] (22)

However, these functions work only in the case of a 5 rings discretization. Hence, it has been decided to define a function that readjust the induced velocity no more with the number of the ring but considering the position along the blade span. The readjustment is made only on the last 30% of the blade.

In the previous calculations, the ring 4 was at 77% of the blade and the ring 5 was at 92%.

Hence, making a linear interpolation

\[ \Delta V_i(V_i, W) = \frac{\Delta V_{i5}(V_i, W) - \Delta V_{i4}(V_i, W)}{0.92 - 0.77} \times \left( \frac{V_i}{0.77} + \Delta V_{i4}(V_i, W) \right) \] (23)

The propeller thrust

As it has been seen in the part about the calculation of the induced velocity, the thrust of the propeller (calculated on a ring) can be written either using the Bernoulli’s formula (17) or making a local calculation on a blade element (18).

Then

\[ T_h = \sum T_a(V_i) \] (24)

In the code, the equation (17) has been used, but the results would have been identical using (18) as the Newton’s algorithm tends to equalize these two formulations.

The shroud thrust

In order to model the shroud thrust, it has been chosen to use the formula of the lift of a classical airfoil as

\[ \frac{1}{2} \rho S_{shr}[V_i(\text{LastRing}) + W]^2 C_{zshr} \] (25)

where \( S_{shr} \) represents the surface of the shroud and \( C_{zshr} \) the thrust coefficient. The velocity used is the induced velocity calculated on the last ring, which is the closest to the shroud. The lateral wind velocity is also taken into account.

The value of the \( C_{zshr} \) has been chosen in order to match the bench polar that is considered as the best reference. The best value is 0.9.

In the case of left lateral flight, it has been decided to decrease the value of \( C_{zshr} \) as function of the width of the flow channel. The decay of the \( C_{zshr} \) is modeled linear as the \( C_z \) of a classic airfoil decreases linearly when the angle of attack decreases.

\[ C_{zshr} = \begin{cases} -0.9 \frac{w}{W+V_i} + 0.9 & \text{if } V_i > 0 \\ 0 & \text{otherwise} \end{cases} \] (26)

Regarding the right lateral flight (wind on the side of the diffuser), the notion of flow channel being less obvious, the \( C_{zshr} \) is maintained at its hover value, that is to say 0.9. In the reality, a recirculation appears for strong wind in this condition and it changes the behavior of the Fenestron.

Eventually it is considered that the shroud thrust disappears entirely when the flow goes from the diffuser to the collector. This consideration comes from the fact that the lips of the collector are the causes of the shroud and when the flow goes backwards, they don’t have any influence anymore.
In the case of **forward flight**, the formula of the elliptic wing of Prandtl used in the model type 2 is kept (see equation (12)). The function \( k(\epsilon) \) is however modified in order to match the wind tunnel polars in forward flight. It gives:

\[
k(\epsilon) = \begin{cases} 
0 & \text{if } \epsilon' = \frac{\nu_i}{\nu_f+\nu_i} > 2 \\
1 - \frac{\epsilon'}{2} & \text{otherwise}
\end{cases}
\]  
(27)

This function allows a transition between hover and forward flight but also with vertical flight.

However, the equation (25) must be cancelled in order to avoid taking into account two times a shroud thrust. To do this, we place a factor \((1-k(\epsilon))\) beside it.

Finally, the shroud thrust formulation is:

\[
F_{shr} = \frac{1}{2} \rho s_{shr} [V_i (LastRing) + W]^2 
+ C_{zshr} (1 - k(\epsilon)) 
+ \sum_{\text{rings}} 2 \rho k(\epsilon) S a. \sin(\xi) \|V_i\| \cos(\xi) \cdot \overline{V_a} - \overline{V_i} \|V_a\|
\]

**To summarize**

- **Induced velocity calculation**

The induced velocity calculation is made applying a Newton algorithm with the system of equations given by (17) and (18) with,

\[
\tan \alpha = \frac{V_i + W}{\omega r}, \quad C_{xa} = 0.1 \text{ and } \sigma = 1
\]

- **Thrust calculation**

\[
F = \left\{ \begin{array}{l}
\sum_{\text{rings}} q V_{ox} (1 + k(\epsilon) \sin(2\xi)) \\
\sum_{\text{rings}} q V_{oy} (1 + k(\epsilon) \sin(2\xi))
\end{array} \right.
\]

\[
F_{en} = F_{rot} + F_{shr}
\]

With:

\[
F_{rot} = \sum_{\text{rings}} T_a (V_i + \Delta V_i \left( \frac{r}{R}, V_i, W \right))
\]

\[
F_{shr} = \frac{1}{2} \rho s_{shr} [V_i (LastRing) + W]^2 
+ C_{zshr} (1 - k(\epsilon)) 
+ \sum_{\text{rings}} 2 \rho k(\epsilon) S a. \sin(\xi) \|V_i\| \cos(\xi) \cdot \overline{V_a} - \overline{V_i} \|V_a\|
\]

**Results**

**Induced velocities, CFD**

The results given by the new model in term of induced velocity at hover are now very satisfying as shown in Figure 13 compared with the results given by the model type 2 (Figure 9).

Considering lateral flight, the functions DVI ((21) & (22)) improve the matching between HOST and the CFD (see Figure 14).

In this study, the readjustment of the positive induced velocities has been highlighted (from the collector to the diffuser) and the function (23) doesn’t have any impact when the flow goes in the other direction. Indeed, it has been considered that the effect of the shroud is created by the lips at the inlet of the collector.

---

**Figure 13**: Induced velocity calculated by the New Model (5 & 10 rings) vs CFD
Improving the modeling of the Fenestron – R.HUOT - Eurocopter

Figure 14: Influence of DVI on the induced velocity for right lateral flight

However, even if the model doesn’t match with the negative induced velocities, the polars are very satisfying.

Flight tests

In order to validate the model, comparisons have been made with the previous model and some static flight tests. The results are summarized in the Table 1.

<table>
<thead>
<tr>
<th>Flight Test</th>
<th>HOST Type2</th>
<th>HOST NM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hover</td>
<td>76.043</td>
<td>77.424</td>
</tr>
<tr>
<td>Hover</td>
<td>84.186</td>
<td>83.904</td>
</tr>
<tr>
<td>Vy</td>
<td>42.888</td>
<td>41.141</td>
</tr>
<tr>
<td>V=16kt</td>
<td>76.934</td>
<td>81.421</td>
</tr>
</tbody>
</table>

Table 1: Comparison of DDN values

The values are very close to the values obtained using the model type 2 who was already satisfying for hover and forward flight.

Bench and wind tunnel tests

Another way to test the reliability of the model is to compare the polars $F_{fen,θ}$ calculated by HOST with the polars from the Wind tunnel and bench tests.

Figure 15: Polar at hover of the Fenestron 1

However, one should not forget that the new modeling is based on the Fenestron 1 data. Indeed, the function (23) and the value of the $C_{zhθ}$ have been chosen to match the CFD results and the bench polar of the Fenestron 1. Thus, it is interesting to see the reliability of the new model on another Fenestron.

Figure 16: Polar at hover of the Fenestron 2
Improving the modeling of the Fenestron – R. HUOT - Eurocopter

Even for the Fenestron 2, the new modeling seems better than the model type 2. Especially considering the bench test polar which is considered as the best reference. However, for high values of blade pitch, the comparison with the wind tunnel test polar is less satisfying. But it may be explained by the point at 45° that can be a stalled point. If so, the interpolation between this point and the point 30° can distort the real trend.

The polar with lateral flight gives also a very good tendency compared with the previous model.

Mapping

By making simulations with a full helicopter using a Fenestron 1, maps function of the azimuth and the speed of the wind have been drawn.

The decay of the pitch observed for right lateral flight can be explained by the raise of the aerodynamic forces acting on the rudder and on the fuselage. For pure right lateral flight (KHIW=90°) and 47 kt of wind, these forces compensate completely the torque created by the rotor. And beyond this value, the pilot even has to counter them.

Conclusion

The static modeling of the Fenestron has been enhanced by keeping in mind the importance of the physics:
- The flow contraction and the $C_{za}$ of the blades have been reset to their physical values.
- The calculation of the induced velocity has been modified in order to be valid in every flight condition.
- The thrust of the shroud and of the propeller have been dissociated and give coherent results compared with the bench tests and the CFD analysis.
- A readjustment function of the induced velocity has been modeled to take into account the effect of the shroud on the tip velocities.
- Based on the Fenestron 1, this function still gives good results on the other aircraft.
Ways of improvements are however still numerous: the readjustment function (23) could be replaced by a physical analysis of the flow around the shroud and the expression of the shroud thrust, simplified in this modeling, could be reformulated.

**Acknowledgements**

The author wants to thank C.S and T.N, supervisors of this Master thesis at Eurocopter for their help throughout this project, Ulf T Ringertz, Flight Mechanic teacher and supervisor at the Royal Institute of Technology of Stockholm, and all the people of the Flight Mechanics and Loads department of Eurocopter for their support and their advices.

**References**


[18] G. Legras, X. Cottenot, *CFD study of the fenestron shroud design*, U002A0510E01_TN_E_00, July 2012