ORNICOPTER MODEL GROUND TESTING AND THE EFFECTS OF FLEXIBILITY

Dennis J. van Gerwen[1], Theo van Holten[2]

Delft University of Technology
Faculty of Aerospace Engineering
Kluyverweg 1, 2629 HS Delft, the Netherlands
[1]e-mail: d.j.vangerwen@tudelft.nl,
[2] e-mail: t.vanholten@tudelft.nl

Key words: ornicopter, rotor, blade, model, dynamics, test

Abstract. The Ornicopter is a single rotor helicopter that does not produce a reaction torque and therefore does not need a tail rotor or similar device. Forced flapping of the rotor blades is used to control the yaw motion of the aircraft.

This paper describes a test of this yaw control method performed with the radio controlled Ornicopter demonstrator model. Test data show that the forced flapping method works quite well at relatively low thrust levels, but data for the higher thrust levels required for flight are not available yet. Data also show that effects of flexibility in the forced flapping system may pose some limitations on the operation of the demonstrator model, due specifically to the way forced flapping is implemented in this model.

Existing blade theories for the Ornicopter do not predict these effects with sufficient accuracy. In an attempt to gain more insight into these flexibility effects a simple qualitative study of blade dynamics has been performed with the help of multi-body dynamics software. The effects of lead/lag freedom, pitch and torsional flexibility and blade bending on the effectiveness of forced flapping were investigated using a simplified representation of a flexible rotor blade.

The results of this investigation indicate that the fidelity of Ornicopter blade models could be much improved by taking into account pitch flexibility and blade torsion effects. Furthermore, based on these results it is expected that some of the practical problems encountered during testing could be solved by equipping the Ornicopter demonstrator model with lead/lag hinges.

1 INTRODUCTION

1.1 The Ornicopter

Most helicopters today are equipped with a tail rotor or similar device in order to counteract the reaction torque generated by the main rotor and to enable yaw control. The tail rotor, however, has many drawbacks; it is noisy and dangerous to bystanders, it is vulnerable, it wastes up to ten percent of the power available, and last but certainly not least, lack of control authority can arise as a result of adverse wind conditions or interference from the main rotor wake. Perhaps the best way to solve these problems would be to get rid of the tail rotor altogether. For this reason the Ornicopter was devised.

The Ornicopter is a true single rotor helicopter which is fully controlled using only the ‘main’ rotor. A tail rotor is no longer required because there is no reaction torque to be counteracted, and yaw control capability is provided by the same mechanism that prevents the reaction torque from arising.

A radio controlled Ornicopter demonstrator model has been built (Figure 1) and, although the model has not yet been tested in free flight, ground tests have proven that the concept works. The current paper describes the results of a yaw control ground test and investigates the effects of flexibility on the forced flapping principle and on rotor loads. Furthermore some possibilities for increasing the accuracy of theoretical rotor blade models for the Ornicopter are discussed.

But first a closer look at the principle behind the Ornicopter: How can a rotor operate without generating a reaction torque and how can it be used for yaw control?

1.2 Forced flapping

The secret of the Ornicopter rotor is forced flapping. The rotor blades are forced to flap up and down once per revolution using some mechanism. This forced flapping is what drives the rotor. Each revolution the aerodynamic resultant force acting on the blade will be tilted backward and forward, resulting in a decelerating and an accelerating force component respectively, as depicted in Figure 2.

If the correct forced flapping amplitude is chosen (the trim amplitude) the forward component will cancel out the backward component and the average shaft torque is reduced to zero. The effect is similar to that of a tip jet rotor: A driving force arises on the blades which counteracts the drag force, so there is no need for a driving torque on the rotor shaft, and neither will there be a reaction torque on the fuselage.

The theoretical background for the Ornicopter, describing this principle in detail, has already been covered extensively in previous publications([1],[2],[3],[4]). Furthermore, wind tunnel tests and fixed base tests with the radio controlled demonstrator model from Figure 1 have proven that the Ornicopter concept works ([3],[5]).

Although the Ornicopter rotor does not generate a reaction torque obviously some means of yaw control is still required. This is provided by increasing or decreasing the amplitude of the forced flapping motion of the blades. The change in flapping amplitude will cause the rotor to tend to speed up or slow down, and with the help of some kind of speed governor a steering torque can then be generated on the fuselage. The forced flapping amplitude is controlled using the pedals, taking over the role of tail rotor collective pitch.

1.3 Free flapping

In addition to the rather unconventional forced flapping yaw control method, the Ornicopter uses conventional collective and cyclic pitch controls in order to command all other aircraft motions. This implies that, on top of the forced flapping motion, some degree of flapping freedom is required for controllability of the aircraft.

Although forced flapping and free flapping are conflicting concepts, a compromise can be found in the use of some form of flexibility in the forced flapping system, e.g. a spring between the forced flapping mechanism and the rotor blade. In the Ornicopter demonstrator model the flapping freedom is provided in a different way.

Figure 1: The Ornicopter demonstrator model

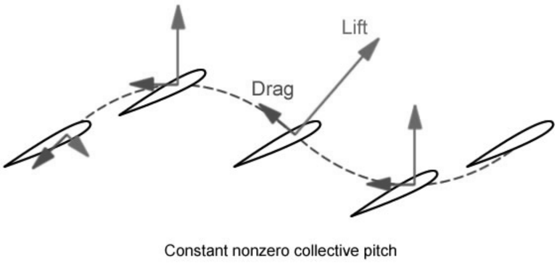

Figure 2: Aerodynamic forces on a blade element during one rotor revolution, due to forced flapping (angle of attack is exaggerated)

1.4 The Ornicopter demonstrator model

The Ornicopter demonstrator model is an off-the-shelf radio controlled model helicopter with a 1.7m diameter four bladed rotor, a modified hub and drive system, and of course without a tail rotor assembly. It was built to show that an Ornicopter can actually fly. A conventional swash plate assembly is used for collective and cyclic pitch control. A forced flapping mechanism incorporated into the rotor hub of the demonstrator model generates a 1/rev sinusoidal root flapping displacement whereas the required flapping freedom is provided by the flexibility of the rotor blades themselves. The use of flexible rotor blades however has some side-effects which will be discussed in the next section.

The amplitude of the forced flapping motion can be adjusted between 9.0° and 12.7°. This limited range of flapping amplitudes is not ideal but is due to the construction of the flapping mechanism. As a result of this limited range the demonstrator model is not able to perform autorotation because that would require the forced flapping amplitude to be reduced to zero. In a full scale Ornicopter this should of course be possible.

Another consequence of the limited range of flapping amplitudes is that the model can only be controlled within a certain range of tip speeds. The flapping range was chosen based on a constant design tip speed around 100m/s (1000 rpm), but because blade flexibility makes it hard to calculate the required trim flapping amplitude, as described in [4], the actual operating tip speed for the model needs to be determined experimentally.

2 DEMONSTRATOR MODEL GROUND TESTING

2.1 Blade flexibility effects

Due to blade flexibility the effectiveness of the forced flapping motion decreases as the tip speed increases. For example, according to calculations based on analytical rigid blade theory and flexible blade theory in hover conditions ([1],[2],[5]) the effective flapping amplitude for a demonstrator model blade at 100m/s is almost half the actual root amplitude. That is, the flexible blade flapping with a root amplitude of 9° has the same effect on shaft torque as a rigid blade with the same properties flapping at 4.5° amplitude. Thus the effective range of flapping amplitudes for the demonstrator model depends on the tip speed. This is depicted in Figure 3 which also shows the calculated trim flapping amplitude based on rigid blade theory. This figure represents an operating envelope for the demonstrator model in hover.

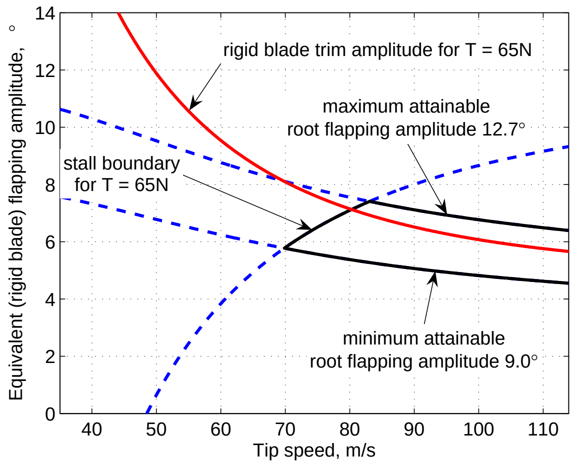

Figure 3: Demonstrator model operating envelope (calculated)

Figure 4: The demonstrator model during a yaw control test

Obviously, for the yaw motion of the model to be controllable, the trim amplitude must be within the effective range of flapping amplitudes, otherwise the shaft torque cannot be reduced to zero. Furthermore, the trim amplitude should be near the centre of the effective flapping range in order to enable a sufficiently large change in flapping amplitude to either side, for the purpose of generating a yaw control torque about the rotor shaft. This is explained in more detail in [5].

Based on Figure 3 a tip speed of 100m/s would indeed seem like a good design point. However, previous tests have shown that the theoretical methods overestimate the effectiveness of flapping by as much as 40% so that Figure 3 should only be used for qualitative reference. In order to determine the best operating tip speed for the demonstrator model, and to investigate further the effects of blade flexibility, yaw control tests have been performed [5].

2.2 Yaw control test in hover conditions

For the yaw control tests the demonstrator model was placed on a turntable supported by a platform scale as depicted in Figure 4, thus providing two degrees of freedom (2DOF). The platform scale was used to measure the rotor thrust whereas the turntable allowed visual observation of the direction and rate of rotation of the fuselage. An optical tachometer was used to monitor the rotor rpm.

The test plan was as follows: For constant tip speed (increasing from 600rpm to 900rpm to 1000rpm) and three different values of flapping amplitude (9.0° or minimum, 10.8° or centre and 12.7° or maximum) the collective pitch was to be increased until the fuselage would remain pointing in one direction, indicating that the reaction torque was reduced to zero and the trim state was reached. Furthermore, at each trim state around the centre of the flapping range the response to yaw control inputs was to be assessed. Unfortunately the test series had to be aborted prematurely due to failure of a pitch link and subsequent damage to the model.

Consequently the thrust level required for flight (65N) was not reached. Nevertheless, the torqueless state was achieved for lower thrust conditions and the yaw control response has been assessed on one occasion. At a tip speed of 52m/s a change in flapping amplitude in the order of 5% of the trim amplitude proved to be enough to achieve yaw rates in the order of 45°/s and even though the control mechanism is very slow (rate of change of flapping amplitude is smaller than 1°/sec) a 90° heading change could be achieved with only small overshoot.

The resulting data for the 2DOF test are collected in Table 1 and they are depicted in Figure 5 together with the results from fixed base tests and the theoretical effective flapping amplitude. It becomes quite clear from the figure that, even though the overall trend seems correct, the effectiveness of flapping is much smaller than predicted by the theoretical models. Also, and more importantly, the effective range of flapping amplitudes decreases much faster than predicted.

So what does this mean for the demonstrator model? First of all selection of a suitable tip speed is even more important than initially anticipated because the operating envelope becomes very limited at higher tip speeds due to the reduced range of effective flapping amplitudes. At relatively low tip speed and thrust level the yaw motion of the model could be controlled quite easily, but it is not yet clear whether the demonstrator model will be controllable at the high tip speeds that are necessary to achieve a thrust large enough to sustain flight (65N).

This will need to be investigated further in the next series of tests, but before these can take place more insight is required into the mechanisms of failure that caused the demonstrator model to break down during the tests. Furthermore, the theoretical predictions for the flapping amplitude are still far from accurate and it would be very interesting to see where the errors originate from.

The most obvious sources of error are the constant uniform inflow and the absence of dynamic stall effects in the aerodynamic model, and the fact that pitch and torsional flexibility, lead/lag motion, and bending/torsion coupling are not taken into account in the structural dynamics model. Furthermore scale effects are also expected to play a role since Reynolds numbers are in the order of 10^5.

Based on previous work the structural dynamics model is believed to be the most limited and therefore deserves more attention. Thus, in order to gain a better understanding of the dynamics of a real Ornicopter rotor blade a qualitative investigation of the effects of forced flapping on the rotor assembly has been conducted.

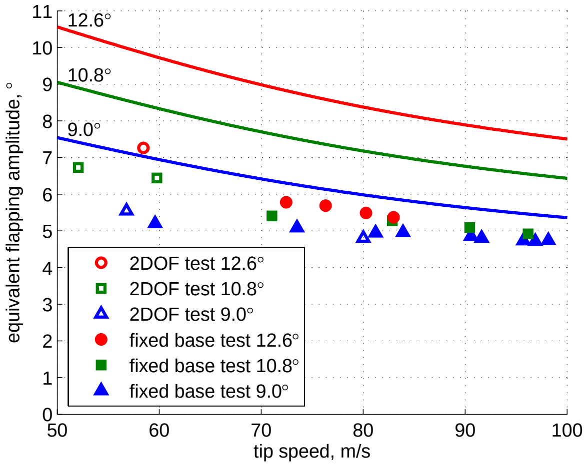

Figure 5: 2DOF test results, fixed base test results, and predicted flapping effectiveness

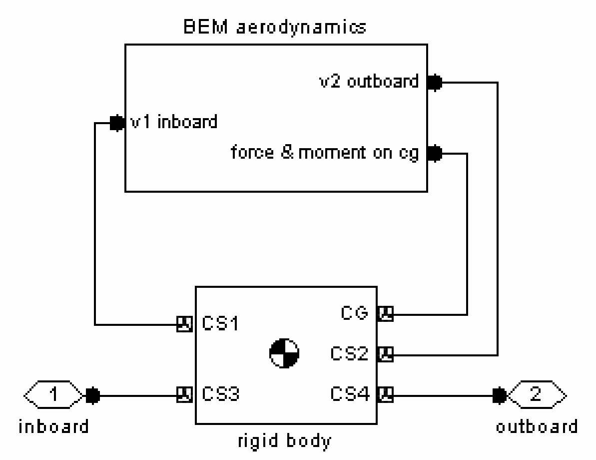

Figure 6: Rigid blade element block in Simulink SimMechanics

Table 1: Measurements obtained from 2DOF test in torqueless state

	rotor speed:	tip speed:	thrust:	root ampl:	equivalent ampl:
	Ω	V_{tip}	T	ε	β_{eq}
	rpm	m/s	N	°	°
#:	measured	ΩR	measured	measured	calculated
1	648	56.8	14.7	9.0	5.55
2*	594	52.1	23.7	10.8	6.44
3	682	59.8	27.8	10.8	6.44
4	667	58.5	36.0	12.6	7.26
5	913	80.0	7.4	9.0	4.81

* yaw control response assessment

3 QUALITATIVE INVESTIGATION OF FLEXIBILITY EFFECTS

3.1 Multi-body dynamics rotor blade model

In order to investigate the effects of blade flexibility on the operation of the Ornicopter demonstrator model, a three dimensional multibody dynamics (MBD) rotor blade model was developed. The MBD model was built in Matlab/Simulink using the SimMechanics package. The model incorporates fully nonlinear dynamics and linearized blade element momentum (BEM) aerodynamics with constant uniform induced velocity (Figure 6). The use of a uniform induced velocity distribution is justified by [3], although at a later stage unsteady aerodynamic effects will also need to be taken into account.

Whereas previous mathematical rotor blade models for the Ornicopter only take into account rigid body flapping and/or out of plane bending ([1],[2],[4]), the primary goal of the current model is to gain more insight into the qualitative effects of not only out-of-plane bending but also lead/lag motion and pitch link (or torsional) flexibility on the effectiveness of forced flapping and on the corresponding loads on the structure. Note that the current MBD model is not intended to be a comprehensive representation of an Ornicopter rotor blade and is therefore only loosely based on the actual rotor blade used in the demonstrator model.

A rigid blade model with hinge offset and rotor diameter equal to those of the demonstrator model is used for comparison. In order to investigate the effects of blade flexibility an equivalent rigid blade with hinge offset and hinge spring is used. This implies that the root flapping amplitude will be underestimated. Accurate representation of root flexibility would require a more detailed model with many more flexible segments near the root, but it is believed that the qualitative flexible blade effects can be captured sufficiently well using this simple representation. The spring stiffness for this quasi-flexible blade was based on the average flexural rigidity of the demonstrator model blade ($EI=12Nm^2$).

The MBD blade model used is depicted in Figure 7. Different configurations can be investigated by fixing specific joints. Only the outboard rigid body has inertial properties (m, I) and aerodynamic properties (cla, cdp). The model has been verified with the help of analytical rigid blade theory for the simple case of a rigid blade with flapping hinge at constant pitch as described in [1]. This can be seen in Figure 8.

Blade configurations considered in the analysis are the rigid blade without lag hinge (F), rigid blade with lag hinge (FL), quasi flexible blade without lag hinge (FF), the quasi flexible blade with lag hinge (FLF), the quasi flexible blade with pitch flexibility (FPF) and finally the quasi flexible blade with lag hinge and pith flexibility (FPLF). The effects of forced flapping on thrust, shaft torque, flapping amplitude, and pitching moment are examined for a rotor similar to that of the demonstrator model (rotor radius = 0.837m) in hover conditions (delivering 65N of thrust).

The pitch degree of freedom can be seen to represent two different effects. It represents the flexibility of the pitch control system but it can also be interpreted as torsional flexibility of the blade. The pitch joint spring stiffness is based on a maximum pitch amplitude in the order of 0.5°.

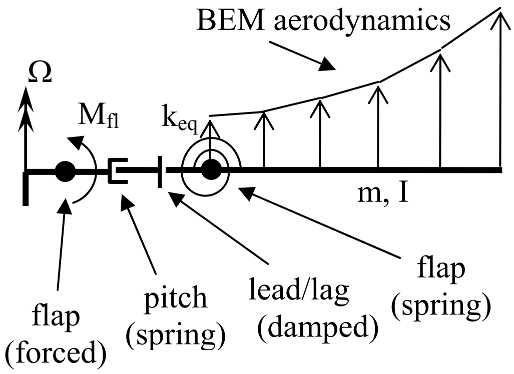

Figure 7: Schematic representation of the quasi flexible MBD model used to represent the Ornicopter blade

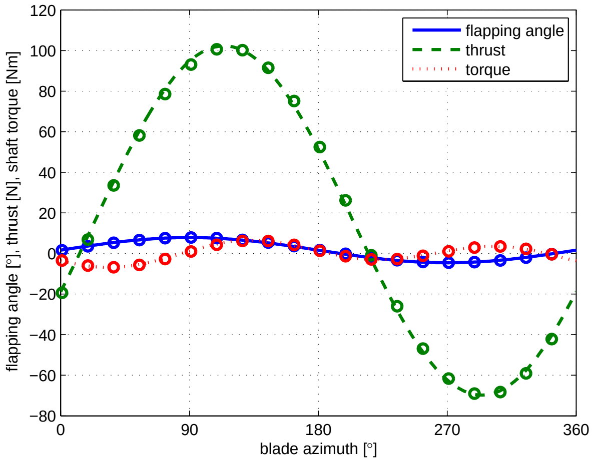

Figure 8: MBD model verification based on rigid blade theory

3.2 Multi-body dynamics results

The MBD rotor blade model used represents a rotor of 0.837m radius with a flapping hinge offset of 11% and a lag hinge offset of 19%, similar to the demonstrator model. The blade is analyzed for the trimmed hover condition, i.e. with zero reaction torque. Six configuration cases are considered. The degrees of freedom for each case are denoted using the capitals F, L, and P, indicating flapping freedom, lead/lag freedom, and pitching freedom respectively. The order of these capitals represents the physical order of the hinges. For example FPF indicates flapping freedom, pitch freedom and then another flapping freedom. The second F refers to the flapping hinge and spring used to represent blade flexibility.

The configurations under consideration are: F, FL, FF, FLF, FPF, and FPLF. Because the current demonstrator model is equipped with only a flapping hinge and a flexible blade (neglecting pitch and torsional flexibility), the FF case is used as the baseline for comparing other configurations.

Looking at blade thrust, depicted in Figure 9, it appears that the quasi-flexible FF blade produces a higher thrust amplitude than a rigid blade (F, FL). This can be attributed to the different distribution of lift over the blade as a result of the phase difference between the blade root and tip. Addition of lead/lag and pitch freedom increase this amplitude even further.

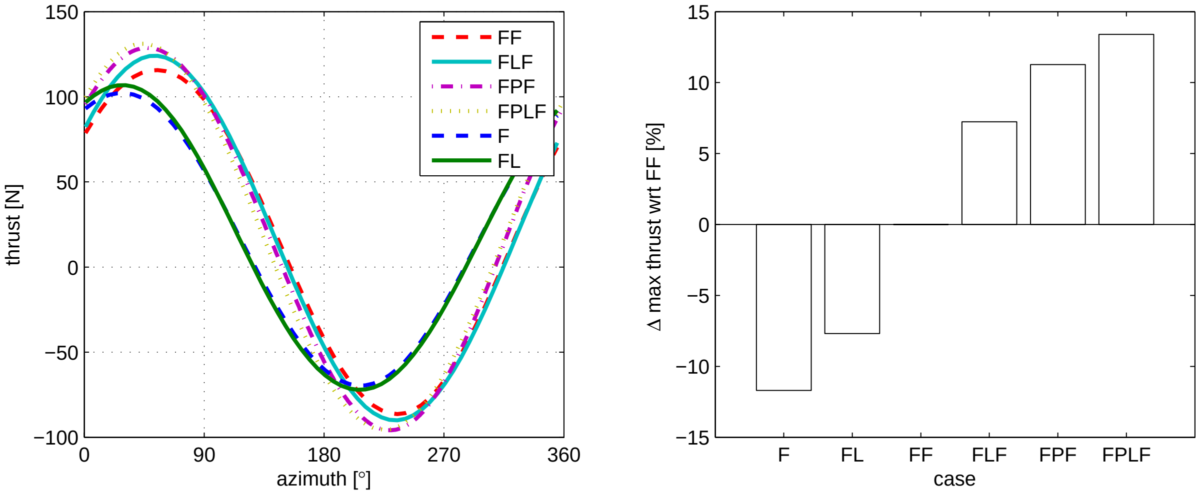

Figure 9: Thrust per blade during one revolution, and maximum thrust comparison (change with respect to case FF)

The maximum reaction torque on the shaft for the FF blade is also much larger than for a rigid blade, judging from Figure 10. Pitch flexibility increases this maximum torque further, as can be seen for the FPF case. Not surprisingly, addition of a lead/lag freedom reduces the maximum reaction torque considerably (that is after all what these hinges were invented for in the first place). What is interesting is that this effect seems to be much more profound for the quasi-flexible blades than for the rigid blade. Of course a lead lag damper will undo the positive effect on reaction torque somewhat.

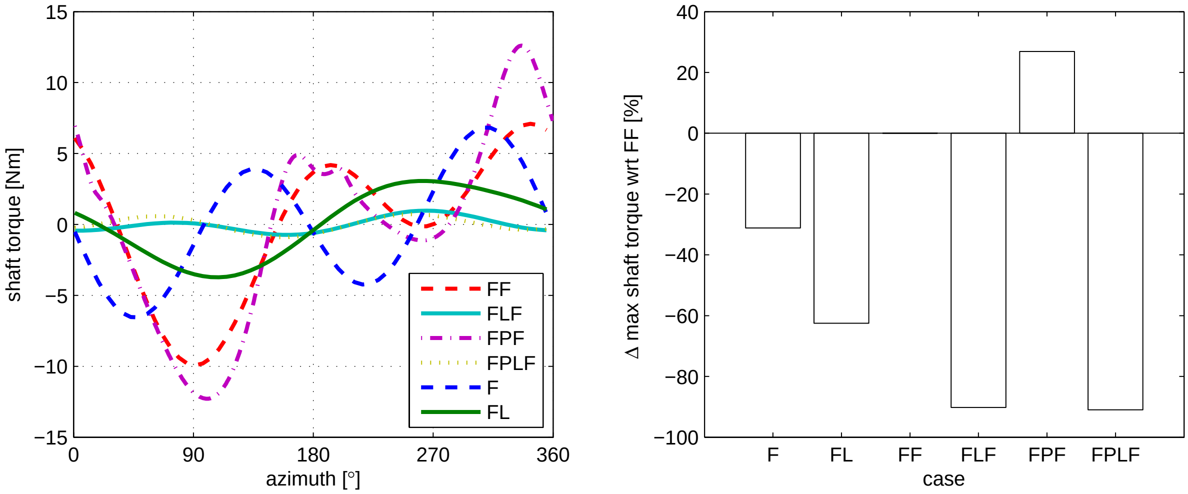

Figure 10: Reaction torque per blade during one revolution, and maximum reaction torque comparison (change with respect to case FF)

As was already known from flexible blade theory, the flapping moment required in the trim condition is smaller for a quasi-flexible blade than for a rigid blade. This becomes very clear from Figure 11. Addition of lead/lag and pitch freedom does not seem to make much difference here.

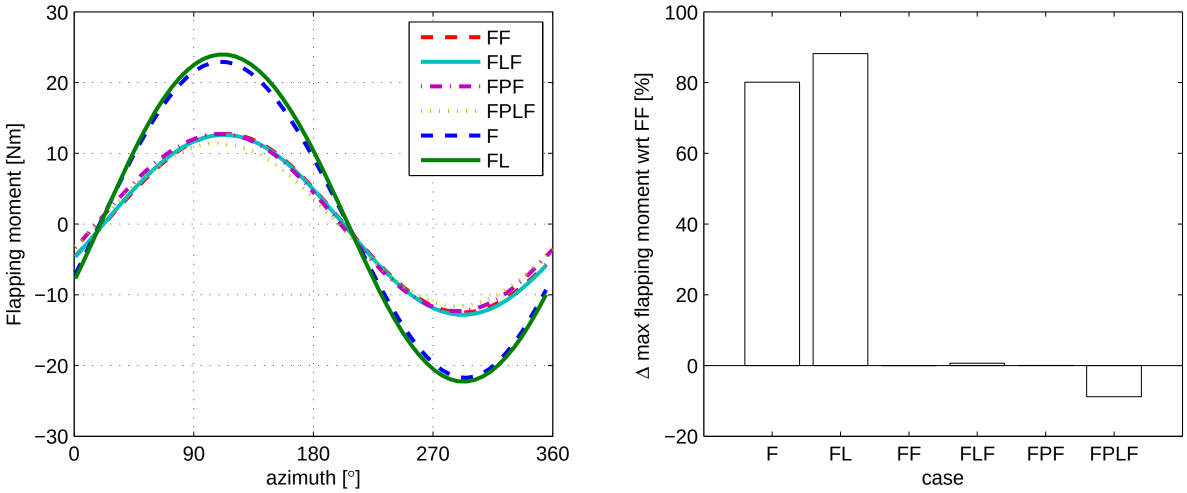

Figure 11: Flapping moment per blade during one revolution, and maximum flapping moment comparison (change with respect to case FF)

As a crude indication of the loads on a pitch link, the pitching moment is displayed in Figure 12. The quasi-flexible FF blade as expected experiences a relatively large pitching moment. This can be explained by the fact that due to the bending of the blade the aerodynamic (drag) forces will generate a moment about the pitching axis. Furthermore, due to the bending of the blade, the mass moment of inertia about the pitching axis becomes much larger.

On several occasions the pitch links on the Ornicopter demonstrator model have come loose during testing, and on one occasion a pitch link even broke. This is probably due to the relatively high loads these links experience as a result of blade flexibility. Figure 12 suggests that addition of a lead/lag hinge at the blade root could reduce the pitch link loading considerably.

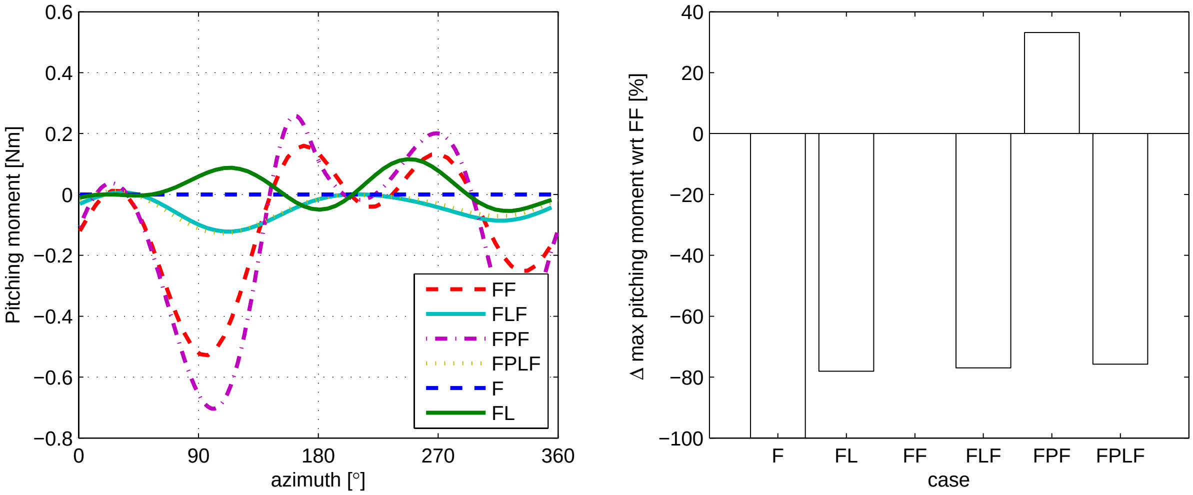

Figure 12: Pitching moment per blade during one revolution, and maximum pitching moment comparison (change with respect to case FF)

The root flapping amplitude for the rigid and quasi-flexible blade cannot be compared because the flexible blade approximation is far too limited. In order to get a better approximation of the actual root flapping amplitude for a flexible blade the model should incorporate many more small bending elements near the root. This becomes apparent when looking at Figure 13. The root flapping amplitude for the quasi-flexible blade is even smaller than that for the rigid blade. This is clearly the other way round in reality.

Nevertheless it is possible to get some indication of the effects of lead/lag freedom and pitch freedom on the flapping amplitude for the quasi-flexible blade. Apparently both degrees of freedom increase the required flapping amplitude, although the effect is limited to an increase of approximately 10%.

Figure 13 also shows the maximum angle of attack at the blade tip relative to that occurring in case FF. The maximum angle of attack in this case is approximately 10°, which in itself does not seem excessive, although for hover conditions this is relatively large. For example, the angle of attack at the tip in hover for a conventional helicopter with the same properties as the demonstrator model would be around 5º.

All in all this implies that taking into account lead/lag and torsion degrees of freedom in a more advanced flexible blade model could lead to better results than those that have been obtained with previous models (e.g. [2],[4]).

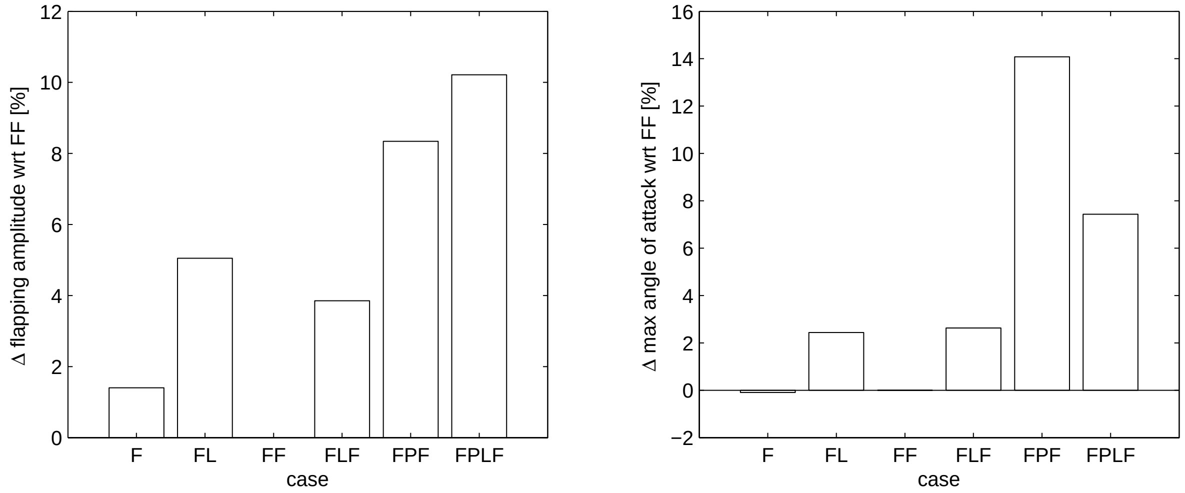

Figure 13: Flapping amplitude required for trim and maximum angle of attack at tip (change with respect to case FF)

4 CONCLUSION

Experiments with the radio controlled Ornicopter demonstrator model have shown that the use of flexible rotor blades as a means of providing flapping freedom can work very well, but it also has some drawbacks. Due to blade flexibility the effectiveness of the forced flapping motion imposed at the root decreases considerably when operating at the high tip speeds required for flight. Although the yaw motion of the demonstrator model has proved to be easily controllable at relatively low tip speeds, the control response at higher tip speeds could not yet be assessed due to practical difficulties. Use of older data suggests however that the region of tip speeds in which the model will be controllable in hover becomes quite narrow. This leads to the question whether the range of flapping amplitudes available for the demonstrator model is wide enough to enable controlled flight.

Theoretical models have not yet been able to predict the required flapping amplitudes with sufficient accuracy to be of practical use here. The most probable cause for this inaccuracy is an over-simplified dynamic model. In order to find out how to improve the theoretical models a qualitative study has been performed. A nonlinear multibody dynamics blade model was employed to gain some insight into the qualitative effects of lead/lag freedom and pitch/torsional freedom on the required flapping amplitudes and on the loads that occur in the forced flapping mechanism.

Although this MBD model is far from comprehensive, and blade flexibility is only represented in a simplistic way, the model does yield some good clues as to the importance of several factors in the modelling of Ornicopter rotor blade dynamics. Although the MBD blade does not prove whether the discrepancy between theory and experiment comes from the structural model or from the aerodynamics model, it does suggest that a more comprehensive flexible blade model with lead/lag freedom and pitch/torsional flexibility could lead to a considerable improvement in the theoretical results.

Furthermore there are some good indications that equipping the Ornicopter demonstrator model with lead/lag hinges could lead to a considerable reduction in pitch link loads and also much smaller peaks in the shaft torque vibration. This will however be at the cost of a slightly larger flapping amplitude and a slightly larger angle of attack.

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