FORCED FLAPPING MECHANISM DESIGNS FOR THE ORNICOPTER: A SINGLE ROTOR HELICOPTER WITHOUT REACTION TORQUE

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Abstract

The Ornicopter is a single rotor helicopter without a reaction torque. By forcing the blades of the Ornicopter to flap up and down, both a lifting force and an average propulsive force can be generated. Because of this average propulsive force the blades will propel (i.e. rotate) themselves and there will no longer be a need to transfer torque from the fuselage to the rotor. If there is no longer a torque transferred from the fuselage to the rotor there will neither be a reaction torque.

This paper will present four mechanisms that have been developed to achieve the necessary forced flapping of the blades. The mechanisms that will be considered are the swash plate mechanism, the eccentric mechanism, the gearwheel mechanism and the multiple disc mechanism.

Introduction

The tail rotor of helicopters, necessary to counteract the reaction torque of the engine and to control the helicopter in yaw, has always been considered a necessary evil. It is expensive, consumes power, has only marginal control authority under unfavorable wind conditions, and is on top of that noisy, vulnerable and dangerous. The ideal solution to all these problems would be to design a rotor that eliminates the need for a tail rotor. The Ornicopter is such a revolutionary design.

The mechanism of the Ornicopter is derived from bird flight. When birds flap their wings they are able to derive both a lifting force and a propelling force out of it. Instead of propelling a helicopter blade by spinning it around and deriving lift from this rotating movement, as is done in conventional helicopter configurations, the Ornicopter flaps its blades like a bird and derives both lift and a propulsive force from this movement. In this case the blades propel (i.e. rotate) themselves and there is no longer a need for a direct torque supplied by the engine to rotate the blades. The fact that the engine torque is no longer directly transferred from the fuselage to the rotor is the key feature of the Ornicopter, and it is this feature that makes the anti torque device redundant.

How lift is derived from forced flapping

As stated before, the Ornicopter should flap its blades like bird wings in order to obtain both a propulsive force that will rotate the blades and a lift force that will keep the Ornicopter airborne. The movement of a bird wing however is extremely complicated and it is impossible to mimick this movement exactly with an Ornicopter blade. But a very useful and simple approximation can be obtained by applying a constant pitch angle to the Ornicopter blade.

The movement of an Ornicopter blade during one revolution is pictured in figure 1. During one revolution of the blade, the blade will be forced to flap both up and down once, resulting in the shown undulating path. If a constant pitch angle is applied the lift forces during one revolution will (averaged over one revolution) result in an upward force and an average propulsive force. This average propulsive force is achieved because the forward horizontal component of the lift force that occurs when the blade is flapping downwards is much larger than the backward horizontal component of the lift force that occurs when the blade is flapping upwards. Thus by setting all the Ornicopter blades at a constant pitch angle and flapping them upwards and downwards a propulsive force is created that will rotate the blades around the rotor hub and an upward force is created that will counteract gravity.

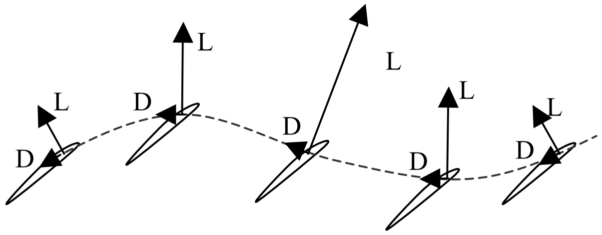

Fig. 1: Lift and drag forces acting on an Ornicopter blade during one revolution when a constant pitch angle is applied.

For a further explanation of the basic principles of the Ornicopter (a calculation of the power required, or an explanation of yaw control, cyclic control and collective control) please see (Ref 1 and 2).

Different flapping configurations

The forced flapping of the blades might cause severe vibrations in the forces and moments that act about the rotor hub. For a feasible Ornicopter concept all the average values of the forces and moments on the rotor hub caused by the entire rotor need to equal zero (except for the vertical force). By choosing an appropriate number of blades and an appropriate flapping sequence of the blades these average values can indeed be reduced to zero (Ref 5). Different flapping configuration and their effect on vibrations have been analysed (Ref 3 and 5). The two most favorable configurations for which corresponding forced flapping mechanisms have been designed will be briefly discussed below.

The double teeter configuration

The double teeter configuration has been chosen as a concept because of the relative simplicity of its forced flapping mechanism. The principle of the double teeter configuration is depicted in figure 2. As indicated by its name, the rotor consists of two teeters: the two opposite blades are connected like a see-saw, which means that if one blade is flapping upwards, the opposite blade is flapping downwards. All four of the blades are forced to flap with a 1-P frequency. At the moment in time that one of the two teeters is at its maximum flapping angle, the other teeter will be in the neutral position, as shown in figure 2. The tip path planes of the two teeters are anti-symmetrically tilted with respect to the shaft.

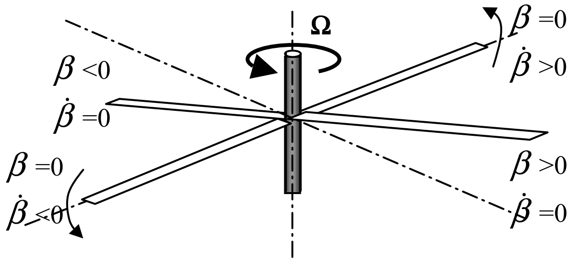

Fig. 2: Principle of the double teeter configuration

The 2x2 anti-symmetrical configuration

Although the forced flapping mechanism of the 2x2 anti-symmetrical configuration will be more complicated than that of the double teeter configuration, this configuration is considered because of its favorable vibration characteristics (only a 2-P vibration in the torque around the hub (Ref 5)). The rotor in anti-symmetrical configuration consists of four blades as well, but now the two opposite blades are flapping in the same direction. So (looking at figure 3) if blade *k=0* is flapping upwards, blade *k=2* is flapping upwards as well, while at the same time the two other blades will be flapping downwards, and vice versa. The blades will pass through the neutral position at the same moment in time.

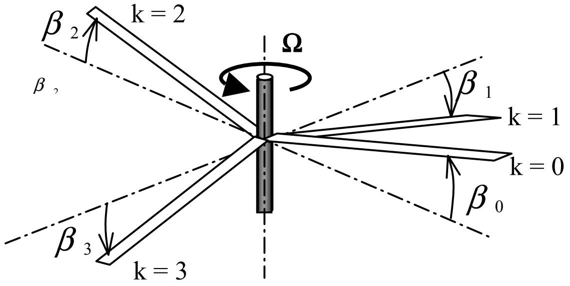

Fig. 3: Principle of the 2x2 anti-symmetrical configuration

Forced flapping mechanisms

The remainder of this paper will now concentrate on how exactly the forced flapping of the Ornicopter blades can be achieved for the different configurations. A forced flapping mechanism should be simple in design, robust, as light as possible and should assure an exact 1-P excitation of the blades.

During the last couple of years different forced flapping mechanisms have been designed, each for a different purpose: a demonstration model, a fixed-base windtunnel model, a free flying scale model and a fixed base full scale model. The following paragraphs will describe each of the developed mechanisms: the swash plate mechanism, the eccentric mechanism, the gearwheel mechanism and the multiple disc mechanism.

The Swash Plate mechanism

The swash plate mechanism (Ref 3) consists of two thin section bearings (ball bearings with the shape of a large ring) see figure 4. These two bearings have different diameters: one bearing fits within the other bearing. Each Ornicopter blade is connected to one of the bearings by a flapping link. When the swash plate has an inclination, the flapping link will glide along an inclined plane, thus forcing the blade it is connected to, to flap up and down with a 1-P frequency.

Both section bearings can be rotated around the same horizontal axis (see figure 4), this way the inclination of each swash plate can be adjusted separately and the orientation of the swash plates with respect to one another can be changed. The swash plates can be rotated anti-symmetrically as shown in figure 4, but they can also be aligned implying that both swash plates are located in the same tilted plane.

The engine drives the rotor shaft, and this will cause the rotation of the flapping links. During rotation the flapping links are forced to glide along the section bearing and will follow the inclined plane, forcing the blades to flap up and down. As explained earlier, this forced flapping will provide both the lift force and the propulsive force which will rotate the blades.

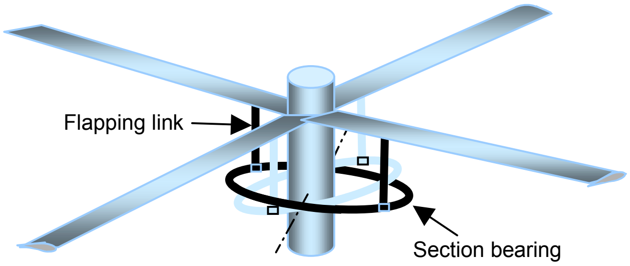

Fig. 4: Schematic representation of the swash plate mechanism

The rotor shaft is in this case driven by the engine, which might make it difficult to believe that there is no torque transmitted to the rotor and no reaction torque acting on the fuselage. However if the *rotor* is still entirely driven by the flapping of the blades (which means that the drag on the blades is counteracted by the forced flapping of the blades implying that there is no need to supply an extra external torque from the fuselage to the rotor), this means that there is no reaction torque. What actually happens is that the rotational energy of the engine that is transmitted to the rotor shaft is transformed into translation energy by the swash plate and this translation energy is transmitted to the rotor.

So, then what happens to the engine torque that is driving the rotor shaft if it is not transmitted to the rotor? It can be calculated (Ref 4) that the forces that are exerted on the section bearings exactly counteract the torque that is produced by the engine. This corresponds to the statement made earlier that the rotational energy is transformed into translational energy by the swash plate: the ball-bearing on the swash plate counteracts the engine torque and produces a vertical fluctuating force that moves the Ornicopter blades upwards and downwards. The engine torque is thus counteracted within the fuselage.

In general, for all other forced flapping mechanisms it can be stated that if the rotor is entirely driven by the flapping of the blades the engine torque will be counteracted within the fuselage and the reaction torque from the rotor on the fuselage will be absent.

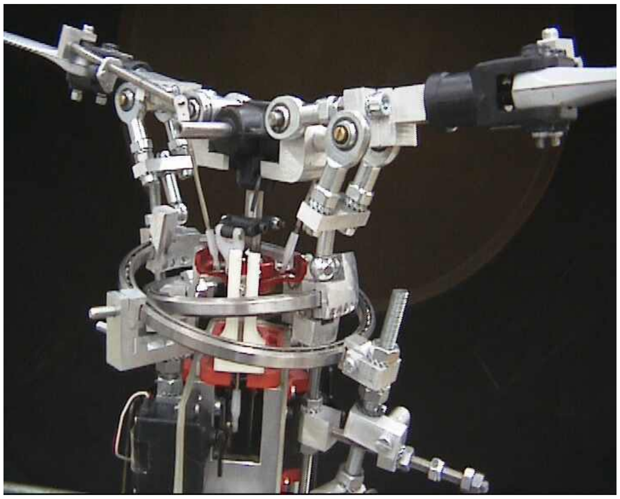

Fig. 5: Windtunnel model with swash plate mechanism, 2 blades (anti-symmetric)

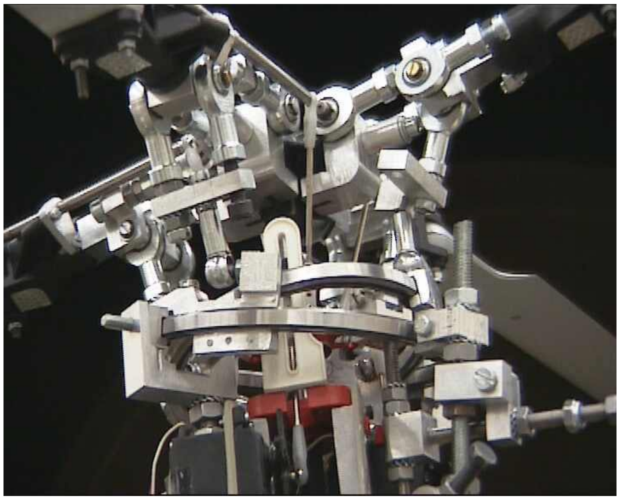

Fig. 6: Windtunnel model with the swash plate mechanism, 4 blades (double teeter)

Now, back to the swash plate mechanism: depending on which blade is connected to which section bearing and depending on how the section bearings are rotated with respect to one another, different flapping configurations can be achieved. The examples in figures 4 and 6 show the double teeter configuration. Another flapping sequence that can be achieved with the swash plate mechanism is a two-bladed anti-symmetrically flapping configuration (see figure 5): the rotor consists of two blades and one blade is connected to the inner bearing, the other blade is connected to the outer bearing. This results in both blades flapping upwards and downwards at the same moment in time (see figure 5). If the two swash plates in figure 5 would be rotated in the same direction and would be aligned this would result in a single teeter rotor.

With the current design of the swash plate mechanism it is not possible to achieve a 2x2 anti-symmetrical configuration.

The swash plate mechanism has been used for the fixed base windtunnel model (see figures 5 and 6, for a movie of the windtunneltest see (Ref 6)). A Vario four blade rotor (a hingeless rotor with a high lead-lag damping) has been modified to incorporate the swash plates. The original shaft has been replaced with an extended shaft yielding a stronger and stiffer shaft, and extra space between the fuselage and the rotor plane.

The extra flapping hinge which is necessary for the forced flapping motion is placed in between the existing feathering hinge and lead-lag hinge. Resulting in the following sequence: lead-lag hinge, flapping hinge, feathering hinge see figure 7. The root of the blade provides the additional necessary flapping freedom.

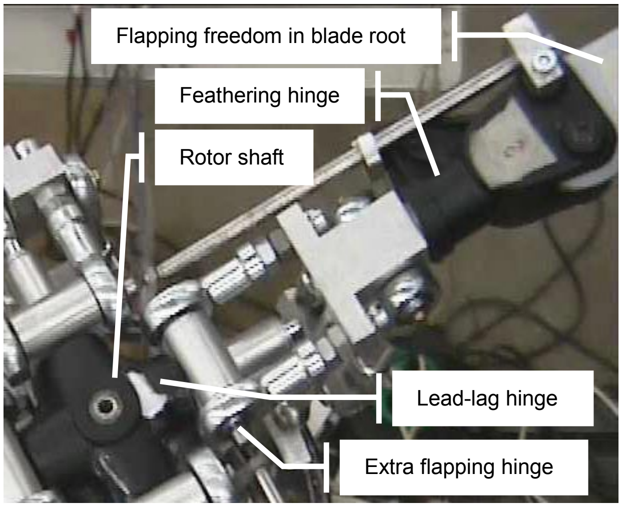

Fig. 7: Hinge sequence for swash plate mechanism

For pitch control of the Ornicopter rotor the pitch control of the original helicopter is used. The pitch horns are extended to the flapping hinge axis to prevent pitch flap coupling, see figure 7.

The main goal of the windtunnel tests was to prove that the Ornicopter concept does not only work in theory but actually works in practice. The windtunnel tests indeed showed that zero torque can be achieved by forced flapping of the blades. The swash plate mechanism performed very well. The only drawback was that the adjustment of the flapping mechanism was very laborious, this due to the precision with which this needs to be performed since small deviations from the desired setting can cause large vibrations. The orientation of the swash plates (to achieve larger or smaller flapping angles) could only be changed when the blades were not rotating. When a mechanism is incorporated that can adjust the orientation of the swash plates while the blades are rotating, the swash plate mechanism can also be used for a realistic full-scale rotor, although it will be complicated.

The Eccentric Mechanism

Another forced flapping mechanism that has been designed is the eccentric mechanism, this mechanism has been especially designed for the double teeter configuration. As the name already leads one to suspect, the mechanism is placed at a certain distance from the rotor axis (the eccentricity, ‘e’), see also figure 8. The mechanism exists of a cross and four linear springs, which are at one side connected to the cross and at the other side connected to the blades. The midpoint of the cross is attached to the fixed shaft, and will therefore remain at the same position, and will not rotate around the rotor axis. The cross however can rotate around its own midpoint.

The blades are attached to the rotating shaft (a hollow shaft since there is a fixed shaft inside), and again this shaft is driven by the engine. For clarity, in figure 8, all blades are drawn as if they were attached separately to the rotating axis. Bear in mind however, that in reality this is not the case. The rotor consists of two teeters which means that blades k=0 and k=2 are connected (and attached to the rotating shaft) and that blades k=1 and k=3 are connected (and attached to the rotating shaft).

If the eccentricity is chosen to be equal to zero, the midpoint of the cross will coincide with the midpoint of the fixed axis. As a result the length of the linear spring will stay constant during a revolution since the distance between the attaching point at the cross and the attaching point at the blade will remain constant. In this case the blades are not forced to flap and will remain in their neutral position.

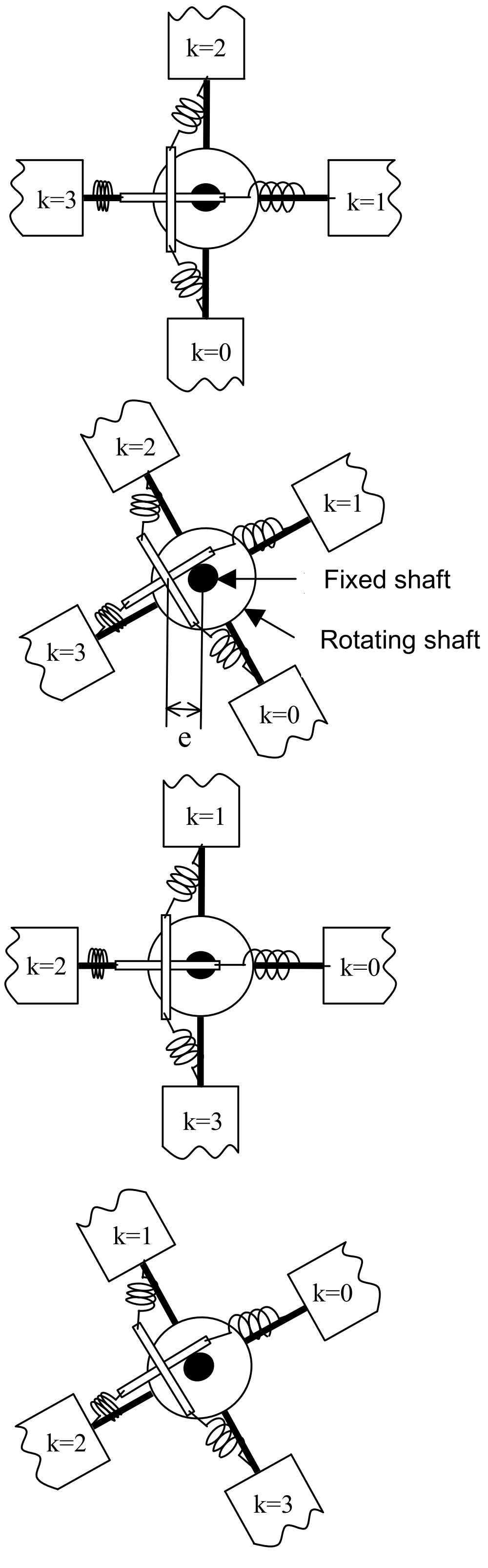

Fig. 8: Eccentric mechanism lay-out, top view.

If the eccentricity is chosen to be as in figure 8, the length of the linear spring will vary during a revolution. If the blade is on the left hand side of the shaft the spring will be compressed, if the blade is on the right hand side of the axis the spring will be stretched. The stretching and compressing of the springs will cause forces in the springs, and thus forces on the Ornicopter blades. These forces will cause the blades to flap. The blade will reach its maximum upward or downward flapping angle 90 degrees further in the rotation than where the maximum force has been exerted.

The magnitude of the flapping can be controlled by adjusting the eccentricity, see figure 9. Increasing the eccentricity results in larger forced flapping angles, decreasing the eccentricity results in smaller flapping angles.

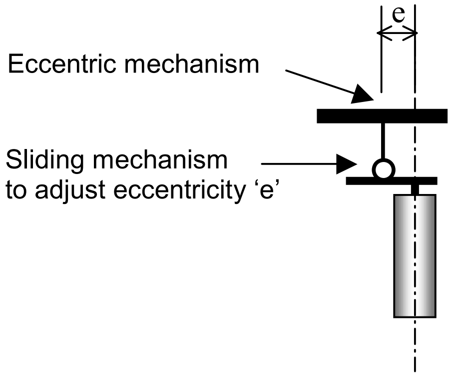

Fig. 9: The eccentric mechanism is attached to the fixed axis, and will therefore not rotate around the axis. The eccentricity can be adjusted by moving the eccentric mechanism along a slide.

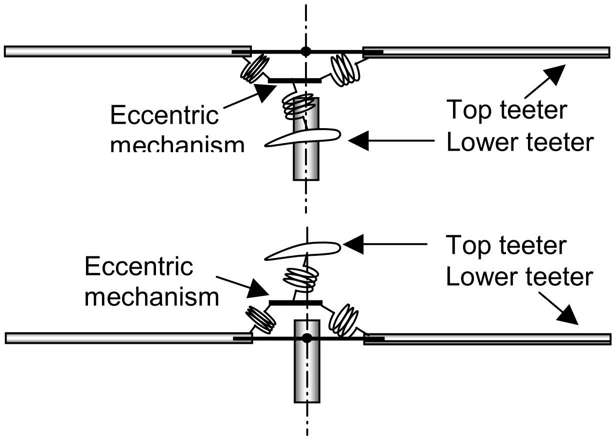

Fig. 10: Principle of the eccentric mechanism, side-views 90° apart.

As can be seen in figure 10, the two teeters are mounted on top of each other, and the eccentric mechanism is added in between. Two of the four springs are therefore directed downwards from the eccentric mechanism, and two springs are directed upwards. This means that if the spring that is directed upward to one of the blades of the top teeter is stretched, it will cause that blade of the teeter to flap downwards. If the spring that is directed downward to one of the blades of the lower teeter is stretched it will cause that blade of the teeter to flap upwards. When returning to figure 8, this means that if a blade of the top teeter arrives at the right hand side of the axis, and the spring is stretched, that blade will start to flap downwards; if a blade of the lower teeter arrives at the right hand side of the axis and the spring is stretched, that blade will start to flap upwards. A double teeter configuration has thus resulted.

This flapping mechanism has been used for the fixed base demonstration model of the Ornicopter (see figure 11). This demonstration model has a very low rotational speed and its function is to show the flapping of the blades and the working of a flapping mechanism.

For the demonstration model this flapping mechanism works very well, and the relative simplicity of this mechanism is definitely a major advantage. The forced flapping motion is automatically synchronized with the 1-P frequency and the springs will transfer the forced flapping motion to the blades but will also allow for the additional necessary flapping freedom.

This mechanism has been especially designed for the double teeter configuration, which turned out to yield some unfavorable vibrations. Therefore it will not be used as it is for a full-scale rotor. However, if the mechanism can be adjusted such that it results in a 2x2 anti-symmetrical configuration it is a very good option for a full-scale mechanism.

Fig. 11: Demonstration model of the Ornicopter

<u>The gearwheel mechanism</u>

The third system that has been developed is the so-called gearwheel mechanism. This system was developed for a radio-controlled helicopter model. The off-the-shelf model will be refitted with a new rotor head consisting of the gearwheel mechanism, which will turn the helicopter into an Ornicopter. The mechanism is currently under development, see figure 12. The gearwheel mechanism was developed for the 2x2 anti-symmetrical configuration.

The mechanism consists of a total of ten gearwheels. These gearwheels are placed in two different planes, each consisting of five gearwheels. First, one set of five gearwheels will be looked at. Secondly, the second group will be examined and its relation to the first group of five will be explained.

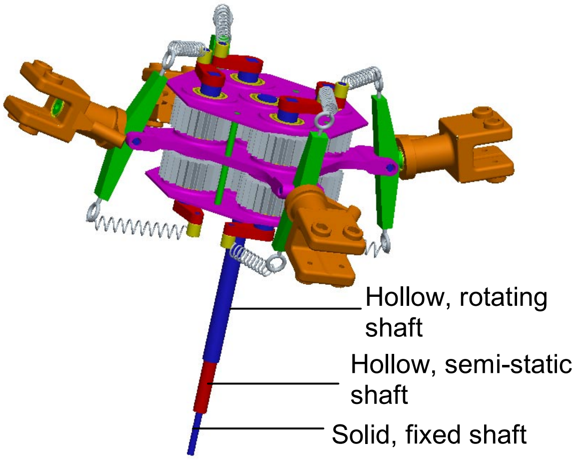

Fig. 12: 3D model of the gearwheel mechanism

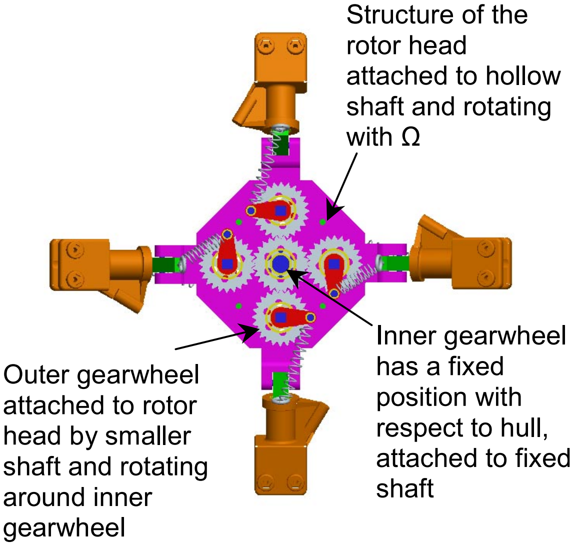

Fig. 13: Top view of the gearwheel mechanism

The upper five gearwheels are being used in a planetary system, see figure 13. This means that four of the gearwheels move around the fifth (and middle) gearwheel. The middle gearwheel is attached to a solid shaft (the inner shaft) that is connected to the hull of the model, see also figure 12. The middle gearwheel will stay locked in the same position with respect to the hull. The outer four gearwheels are connected to the structure of the rotor head by smaller shafts. This structure is connected to a main shaft (the outer shaft) that is rotating at the same speed as the normal rotor shaft in the model helicopter. This shaft is hollow, which allows the fixed shaft to run through. The rotor head is therefore rotating with the normal RPM. This means that the rotor head structure and the four shafts of the outer gearwheels are rotating around the fixed shaft with a certain RPM thereby forcing the outer gearwheels around the fixed, middle gearwheel.

The blade construction is connected to the rotor head, making the blades rotate with the same RPM. There are four blades connected to the rotor head, with each blade at the same angular position as one of the four gearwheels (see figure 13). The shafts of the four outer gearwheels are connected to the rotor head construction and rotate around the fixed shaft with the same speed. This causes the four gearwheels to rotate around that same fixed shaft with twice the rotational speed of the rest of the system. This is due to the fact that all gearwheels have the same radius. During one complete revolution of the rotor head structure, the outer gearwheels have made two complete revolutions around the middle gearwheel.

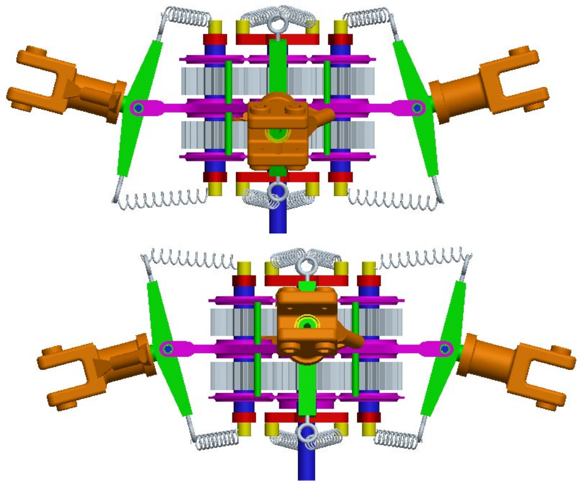

Fig. 14: Side views showing flapping displacements, 90 degrees apart

Each of the outer gearwheels is fitted around a small shaft that rotates around the middle gearwheel as explained earlier, but on top of that also rotates around its own midpoint with the same RPM as the gearwheel it is connected to, see figures 12 and 14. A small lever is connected to each of these shafts and a spring is connected to the end of this lever. The other end of the spring is connected to the upper part of a tumbler that is positioned at the outside of the rotor head. The blade holders are being slid on the small shaft in the middle of the tumbler (see figures 12, 13 and 14).

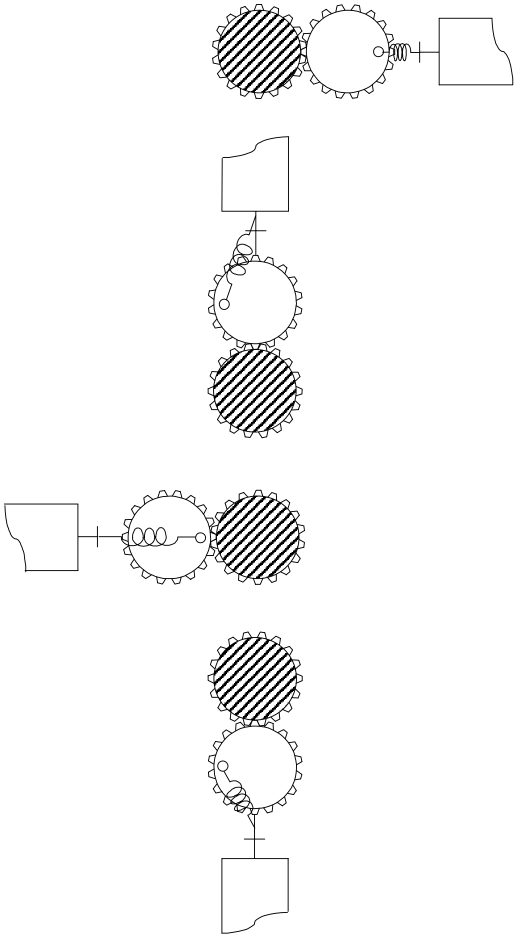

Fig. 15: Principle of elongation of spring, two gearwheels, only top plane

During one complete revolution around the inner gearwheel, the spring reaches one maximum and one minimum length, as depicted in figure 15. The small circle indicates the endpoint of the lever. When the spring is at its minimum length (maximum compression), the tumbler is in its neutral position. At this point a maximum force is being introduced into the tumbler. However, the inertia of the system leads to the tumbler reaching its maximum deflection one quarter of a revolution further. This deflection means that the blade is at the lowest point in its forced flapping trajectory. At the half-revolution point, the tumbler is in its neutral position again while the spring is fully elongated. One quarter of a revolution later, the blade will reach its maximum upward forced flapping position.

This upper plane of gearwheels would, in theory, be enough to introduce the forced flapping into the blades. However, the amplitude of the flapping will have to be controlled to provide yaw controllability. Placing another set of five gearwheels under the first set, will allow for the amplitude to be altered in flight. This can be achieved by placing the rods that are attached to the lower gearwheels in a different phase with respect to the rods of the upper gearwheels.

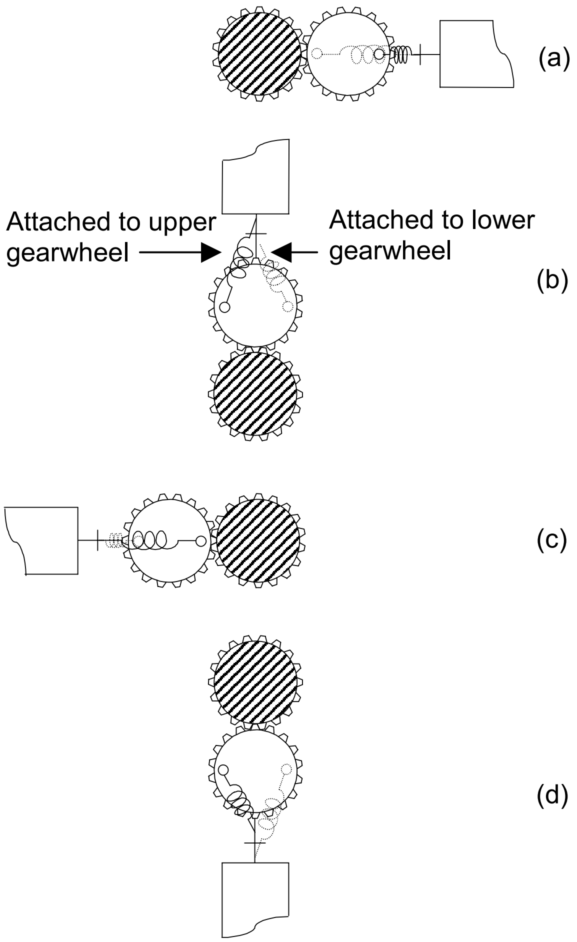

Fig. 16: Principle of elongation of springs, four gearwheels, top and bottom plane.

To illustrate this, an example will be given with the rods placed in exact counter phase. In this situation, the flapping amplitude will be greatest. Figure 16 illustrates how it works. For simplicity, only one blade is looked at. The other three blades go through a similar motion. The dotted components are the components of the bottom set. The small circle again indicates the endpoint of the lever. The patterned gearwheel is the centre gearwheel around which the outer gearwheel is rotating. In subfigure (a) the upper spring is completely compressed while the bottom spring is completely stretched. Therefore, the upper part of the cantilever will feel a maximum force wanting to push the cantilever out, while the lower part of the cantilever will feel a maximum force wanting to pull the cantilever in. This creates a maximum moment around the flap axis. The blade is in its neutral position in subfigure (a).

A quarter of a revolution further (subfigure (b)), the blade will have reached its maximum deflection downwards. The springs are now about the same length (not entirely, for the cantilever is deflected by about 10 degrees). As can be seen, the endpoints of the rods have rotated 180 degrees with respect to subfigure (a). This situation is shown in the upper part of figure 14.

Another quarter revolution further, the blade has returned to its neutral position again (subfigure (c)). Having reached this point, the upper spring is fully elongated while the bottom spring is completely compressed. A maximum flapping moment on the blade is introduced that will flap the blade upwards.

At the three-quarter-revolution point (subfigure (d)), the blade will have reached its maximum upwards deflection. This is also shown in the lower part of figure 14. During the last quarter of the revolution, the blade returns to its neutral position and the springs return to their starting position.

In order to adjust the forced flapping amplitude, the phase difference (which was 180 degrees for the example) will need to be variable. This can be done by adjusting the bottom centre gearwheel with respect to the top centre gearwheel. This means that the bottom centre gearwheel will be semi-static. With respect to the rotating outer gearwheels it will virtually stand still. However, with respect to the top centre gearwheel, it will rotate significantly.

The bottom centre gearwheel is fitted around a shaft (the middle shaft) that runs through the hollow driving shaft, see figure 12. The shaft itself is hollow, so as to allow the solid shaft that is fitted into the upper, centre gearwheel to run through. Small rotations are being exerted on this middle shaft by means of a servomotor. This servomotor is connected to the yaw controls of the helicopter model. Whenever a yaw input is received from either the pilot or the stability system, the phase difference will be adjusted and as a result the forced flapping amplitude will change.

The outer rotor shaft is driven by the engine, just like with an ordinary helicopter. A reaction torque on the fuselage would be expected, but is not present. This means that the flapping system will need to create a torque that counteracts the engine torque within the fuselage itself. The key to this mechanism is the springs. At position (a) and (c) in figure 16, the blades are in their neutral position and the springs are directed in the same line. This situation will not lead to a moment on the fuselage. However, all the other situations do lead to a moment that counteracts the reaction torque. To visualize this, situation (b) will be used to explain how the spring forces result in a moment that counteracts the reaction torque.

In this situation, the spring connections at the gearwheel side are at the same distance from the cantilever rotation point. However, the blade is in its maximum downward position. Therefore the cantilever is rotated approximately ten degrees. The blade will now start to move upwards again. This causes a force in the outer gearwheel as presented in figure 17, which creates a moment on the inner gearwheel. This moment is opposite to the engine torque. By choosing the right springs (spring stiffness) and thus the appropriate flapping moment, the engine torque can be cancelled out.

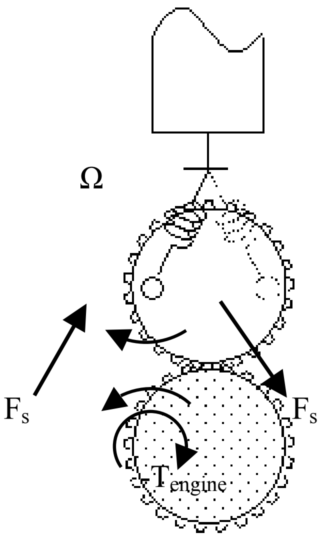

Fig. 17: Schematic representation of forces and moments

The gearwheel mechanism also automatically synchronizes the forced flapping motion with the 1-P frequency. The cantilever acts as a flapping hinge. The standard flapping freedom comes from the flexibility of the blades. The model does not have a lead-lag hinge. A feathering hinge is present inside the blade connection.

The pitch controls will be the same as in a normal helicopter model. A servomotor is connected to the blade connection with pitch links. These links will need to be aligned such that pitch-flap coupling is avoided.

Construction of the radio controlled Ornicopter model will start shortly. Its main purpose is to serve as a visualisation of the Ornicopter principle.

The multiple disc mechanism

The last mechanism, the multiple disc mechanism, has been designed for a full-scale, fixed base test setup of the Ornicopter in double anti-symmetric flapping configuration.

Just as the eccentric mechanism this multiple disc mechanism also uses an eccentricity, but in a slightly different way. The simplification of the model as depicted in figure 18 is used to describe the principle of the multiple disc mechanism. Imagine a rotor with two blades, with a push-pull rod connected to each of the blades. The other end of the rod is forced to slide along the circumference of a static horizontal disc that is situated around the rotor shaft. As long as the disc is centered with respect to the rotor shaft, the blades will rotate without experiencing a push-pull motion, as a result they will rotate in a horizontal plane. However, when the center of the disc disc is moved (translated) to one side, the blades will be pushed up on one side of the disc, and pulled down on the other side (figure 18 is not entirely correct since the phase lag is not incorporated, but it serves quite

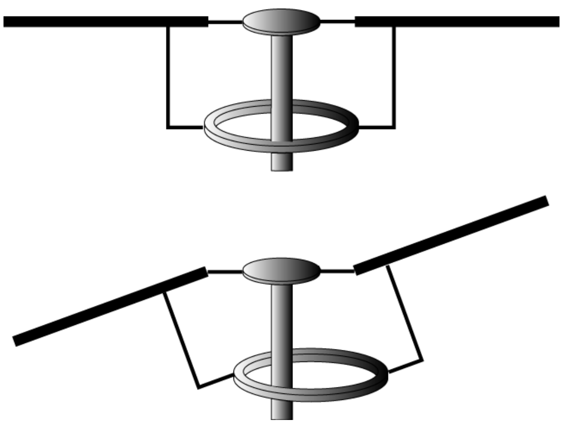

Fig. 18: Flapping principle of multiple disc mechanism

well to explain the principle). When one rotation is completed, both blades will have completed one flapping motion consisting of an up-stroke and a down-stroke.The mechanism used for the full-scale test stand consists of a total of three discs, see figure 19, note that linear springs have also been added in between the push-pull rod and the discs. The middle disc is connected to one of the blades and the top and bottom discs to the other. As the discs move outward, the eccentricity becomes larger and the flapping angle increases.

To achieve an anti-symmetrical flapping configuration the discs are translated with respect to the rotor shaft as can be seen in figure 19. The subfigures in figure 19 together represent one full rotation of the blades, the viewpoint rotates together with the blades as depicted by the arrow.

In subfigure (a) the blades are in the neutral position and the springs are maximally compressed, and the blades will thus experience a maximum force or flapping excitation. Ninety degrees further (in subfigure (b)), the blades will thus have reached their maximum upward flapping angle. One quarter of a revolution further, in subfigure (c), the springs are maximally elongated, which results in a maximum downward flapping angle in subfigure (d), again 90 degrees further.

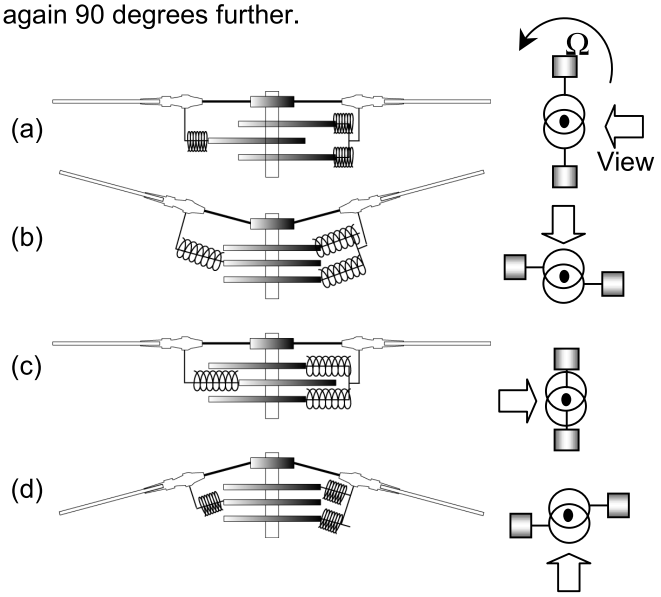

Fig. 19: Multiple disc mechanism during one revolution, two blades different views

To obtain the actual 2x2 anti-symmetric flapping configuration which consists of four blades, a second blade pair is connected to the first by a diamond shaped frame, see figure 20. When the two points connecting the first blade pair move

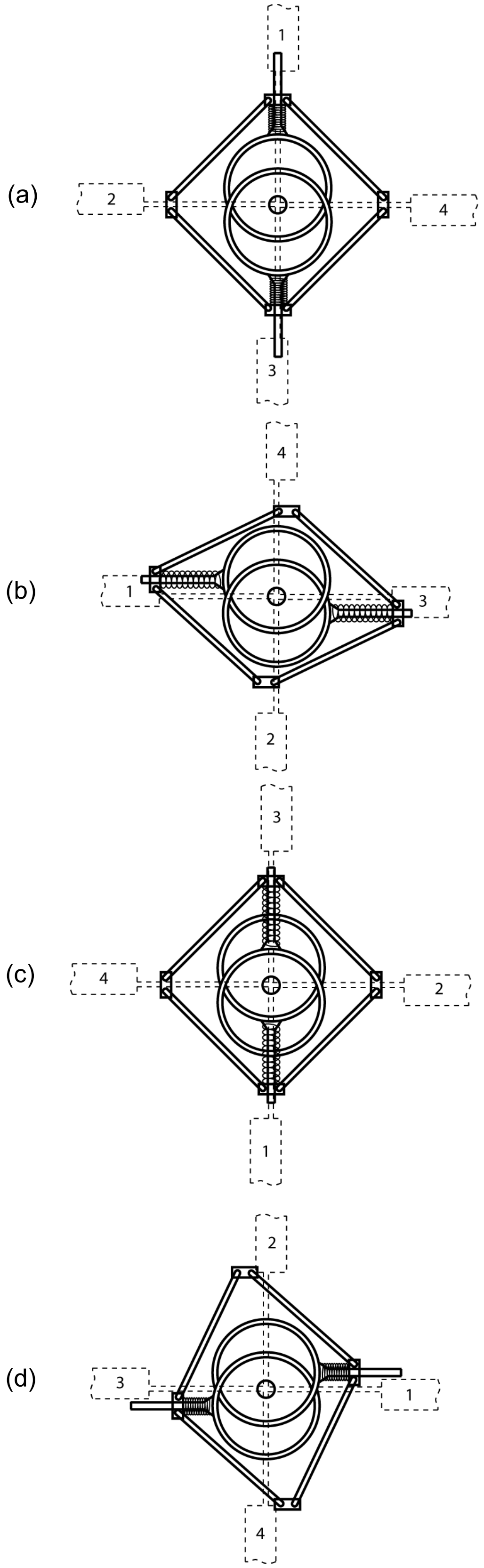

Fig. 20: Multiple disc mechanism during one revolution, four blades, top view

outward, the other two points move inward flapping the blade pairs in opposite directions.

The first blade pair is the master blade pair, since it is directly coupled to the mechanism. The master pair holds blades 1 and 3. The second blade pair is the slave pair. This pair holds blades 2 and 4. Figure 20 shows the complete cycle of the eccentric disc mechanism in each of the four stages of flapping motion.

Figure 20 also explains how the engine torque is cancelled within the fuselage. In subfigures (a) and (c) the forces in the springs do not cause a moment about the rotor shaft. In subfigures (b) and (c) however, a moment is created about the rotor hub by the forces in the springs. By choosing the correct configuration and spring parameters this moment will cancel the engine torque within the fuselage, and the rotor will be without a reaction torque.

Just like the other mechanisms, this multiple disc mechanism also ensures an automatic synchronization of the forced flapping motion with the 1-P frequency. The additional flapping freedom is guaranteed by the springs in the mechanism.

Conclusions

Four different forced flapping mechanisms have been presented. Work is still in progress to fully analyze these mechanisms, to perform calculations and to run simulations. At this moment in time all mechanisms have the potential to develop into a full scale application, the next year will show which mechanism has the most favorable characteristics.

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