Fanning in honey bees—a comparison between measurement and calculation of non-stationary aerodynamic forces

M. Junge
Institute of Structural Mechanics, German Aerospace Center (DLR), Germany.

Abstract

Fanning bees (Apis mellifica carnica) stand on the landing platform at the entrance to their hive and, by beating their wings, produce a current of air that serves to air-condition the hive. They remain up to 5 min on the same spot, so that their regular wing movements present a state of ‘flight’ suitable for study. The three-dimensional kinematic data and the velocity of airflow as well as the produced lift and thrust can be measured directly from individual fanning bees without having to alter their natural behaviour by fixing them. These experimental results allow an assessment of the aerodynamic model calculations which take measured parameters of movement and airflow into account. The reduced frequency, the high amplitude of the wing beat and the form of the trajectory suggest non-stationary aerodynamics. Thus a quasi-stationary and an non-stationary model were tested. The drag and lift coefficients required for quasi-stationary calculations were obtained from the polars of fresh specimens. Nevertheless the quasi-stationary results show that this formulation is not sufficient to explain the resultant aerodynamic forces. The Improved Method of Discrete Vortices was applied for non-stationary calculations. It was possible to model the non-stationary airflow around the virtual oscillating wing (2D), the wake and the resulting aerodynamic forces. The results correspond satisfactorily to the measured values. Based on the simulated vortex pattern and the way the lines of equal pressure and velocities develop it was possible to analyse the effect of inertia, vortices in the wake and the circulation around the wings.

1 Introduction

If the angle of attack of an aeroplane during flight increases very rapidly beyond the critical angle of attack (e.g. the sudden occurrence of vertical gusts or the pitch up of the plane to avoid an obstacle), a strong short-term increase in lift occurs. The forces created by this increase in lift are so strong that it often comes for destruction of the aeroplane. This effect is caused by the non-stationary flow, which is the rapidly changing flow around the aeroplane. The control and, coupled
with this, the exploitation of these very powerful forces—especially under energetic aspects—is very interesting. However, the technical realisation represents a very ambitious task.

Investigations on flying insects can achieve an important contribution to our understanding of the mechanism of non-stationary aerodynamics. During flight insects change the angle of attack, the direction of the motion and the beating velocity of their wings very rapidly, without doing any harm to themselves. It appears that they are able to make use of the non-stationary aerodynamic forces. An exact balancing of the active movements, the form and the material properties of the wings is prerequisite for generating the required kinematics.

In order to avoid the experimental difficulties which arise with free-flying insects, the fanning of honeybees was chosen to represent insect flight. Fanning bees stand on the landing platform at the entrance to their hive and produce a current of air by beating their wings, which serves to air-condition the hive. Since they remain up to five minutes on the same spot by gripping the floor with their claws [1], their regular wing movements present a state of ‘flight’ suitable for studying without fixing the animal. One can observe that fanning bees always arrange themselves in similar formations—in so-called ‘fanning chains’—on the landing platform (Fig. 1). This suggests that the formation is particularly suitable for producing airflow.

2 Results and interpretation of measurements carried out on fanning bees

The measurements were carried out on single bees, as well as on those fanning in chains (Apis mellifera carnica) on a landing platform. In order not to influence the behaviour of the bees or the flow around their wings, the studies were carried out under natural conditions, i.e. the hives were not, for example, artificially heated to stimulate the bees to fan. For experiments which could not be carried out on outdoor hives because of the experimental set-up, a hive was brought into a flight room [3].

2.1 Evaluating of the three-dimensional wing movement

Bees fanning non-stop over a longer period of time on the landing platform were filmed with a high-speed video camera (1000–2000 frames per second). It was possible to see the wing position both from behind and from the side in one frame through a mirror at an angle of 45° to the fanning bee. The following points were digitised in each frame: wing joint G, wing tip S, wing contour and further points of reference. The wing length l of the filmed bees was measured precisely. The digitalised and measured data were used to calculate the three-dimensional movement of the following points and distances on the wing: leading edge point LE and the trailing edge point
TE of the chord, wing tip point S, the point of intersection P of the chord and longitudinal axis of the wing, the length of the chord c, and the distances l_{LE} or l_{TE} from the wing joint to the leading or trailing edge point (position of the points and distances see Fig. 2). The chord cuts the longitudinal axis of the wing at right angles 2/3 l from G.

Even small inaccuracies in the calculated coordinates and the low time resolution greatly distorted the results when calculating the second derivative. Therefore idealised wing beats were calculated for several sequences. Consecutive beats within a sequence were normalised in time ($\Delta t_{\text{beat}} = 1$) and the beats or rather the $x$-, $y$-, $z$-coordinates of the calculated points were projected over one another. The course of the curve is fitted via a polynomial algorithm. The kinematic parameters are calculated from both the idealised and original data. The comparability of different sequences was obtained by standardising of the wing length $l = 1$.

### 2.1.1 Form of the beating trajectory and kinematic parameters

A mean value of 0.62:1 can be calculated for the relation upstroke to downstroke. The beating frequency of individual fanning bees is $f = 118.6$ Hz (standard deviation = 9.8, $n = 37$ bees). This is distinctly lower than the frequency given for flying bees. Also the form of the trajectory differs greatly: at the upper turning point the wing is pulled forward and swings backwards with the beginning of downward motion. During downstroke the wing is moved forwards and down, and during upstroke it is moved backwards and up. The wing moves behind the transversal plane that intersects the wing joint. The angle of inclination $\mu$ of the trajectory (Fig. 2) is $\mu_{\text{up}} = 16.01^\circ$ during upstroke and $\mu_{\text{down}} \approx 14.02^\circ$ during downstroke. (Due to the strong, forward sweeping movement of the wing within the range of the upper turning point, the first third of downward motion and last third of upward motion were not taken into account.) The calculation of the flapping angle $\beta(t)$ (Fig. 3A–C), the sweep angle $\gamma(t)$ (Fig. 4A–C), the geometrical angle of attack $\alpha_{\text{geom}}(t)$ (Fig. 5A), shows that the wing tip, the leading edge point LE and the trailing edge point TE do not reach their minimum synchronously. Thus the wing is never completely motionless at any time. At the upper turning point the minimum and maximum velocity of wing rotation follow one another very rapidly so that very high accelerations are obtained (Figs 3D and 5B).
From the distance between maximum and minimum flapping angle and geometric angle of attack within the wing reference system (wing reference system see sketch Fig. 7), the phase shift between flapping and rotation is calculated. On an average the rotation leads by $\chi_{UT} = 14.6^\circ$ before ‘flapping’ at the upper turning point, and by $\chi_{LT} = 56.1^\circ$ at the lower turning point. The difference in phase correlation occurs since the duration of upward and downward motion is much more asymmetrical than the pronation and supination phases of rotation movements. The difference between the flapping angle of leading and trailing edges during up- and downstroke show that the position of the rotational axis changes during a wing beat. At the turning points it lies close to the longitudinal axis of the wing.

2.2 The effective flow

Created by its movement $\vec{u}$ (the magnitude of $\vec{u}$, see Fig. 6A–C), the flow around the wing takes place at the same speed as its movement, but in the opposite direction. This movement-induced
Figure 4: Sweep angle $\gamma(t)$ at wing tip S (A), leading edge LE (B) and trailing edge TE (C). Points label results of measurement, lines label results based on idealised wing beats.

Figure 5: Geometrical angle of attack $\alpha_{\text{geom}}$ (A) and circular frequency of geometrical angle of attack $\omega_{\alpha_{\text{geom}}} (t)$ (B) at intersection point P. Points label results of measurement, lines label results based on idealised wing beats.
flow is superimposed by the free stream produced by fanning $U_\infty$. The resultant flow around the wing is the effective flow $\vec{U}$.

2.2.1 Speed and direction of the free stream

The speed of flow around fanning bees was determined by using a hot wire anemometer. The measurements were carried out on individual bees and bees standing in a fanning chain. Due to the slow response of the anemometer, only medium flow speed could be registered at several measuring points. Higher values were obtained at all measuring points with bees fanning in a chain than for single bees. In both cases, maximum speeds were measured immediately behind the bee at the height of the upper edge of the abdomen. The maximum difference in flow speed between single and chain bees was measured in front of the head, where the air has at an average speed of $U_\infty^{\text{single}} = 1.29 \text{ m s}^{-1}$ and $U_\infty^{\text{chain}} = 2.24 \text{ m s}^{-1}$ respectively. The higher value in the latter is due to the extra flow coming from a preceding bee.
The direction of airflow was rendered visible by means of wood dust added to the air. No deviation in the horizontal or vertical plane was found in front of the bees. The flow behind the last bee in a fanning chain deviates upwards on an average of 12° (standard deviation 4.1°, n = 52). Comparable, though somewhat higher, deviation values of 10° to 20° were published by Neuhaus and Wohlgemuth [4].

2.2.2 Speed and direction of effective flow around the wing
The effective flow \( \vec{U} \) is calculated by adding the negative vector of movement \( -\vec{u} \) (the magnitude of \( u \) and the velocity triangle see Fig. 6) to the flow \( U_\infty \) measured in front of the bee. It is assumed that flow develops directly from in front (i.e. parallel to the X axis).

The following flow velocities \( U_\infty \) were taken into account in the calculations:

- \( U_\infty = 0 \text{ m s}^{-1} \): no free stream: start of fanning in still air.
- \( U_\infty = 1.29 \text{ m s}^{-1} \): mean velocity of free stream of single fanning bees.
- \( U_\infty = 2.24 \text{ m s}^{-1} \): mean velocity of free stream of fanning bees in chains.

The speed of the effective flow \( U(t) \) is the quotient of the magnitude of the vector \( \vec{U} \) and the time interval \( \Delta t \). Influences from attached or detached vortices could not be taken into account.

A distinct increase of effective flow due to the free stream takes place especially during down-stroke. The forward movement of the wing results in the summation of the two velocity components along the X axis. On the contrary, in the first half of upstroke due to the backward movement of the wings, flow velocity decreases [5, 6].

2.2.3 The effective flow on the chord
To calculate the aerodynamic angle of attack the effective flow on the wing, within the plane in which the chord moves, must be known. The chord moves within the wing reference system (Fig. 7) in the \( X^*Z^* \) plane. The effective flow is thus split into the components \( \vec{U}_{XZ^*} \) in the \( X^*Z^* \) plane and \( \vec{U}_{XY^*} \) in the \( X^*Y^* \) plane.

The vector \( \vec{U}_{XZ^*}(t) \) (Fig. 7A and B) is included in calculating the aerodynamic angle of attack. It proceeds normal to the longitudinal axis of the wing and forms the angle \( \gamma_{XZ^*} \) (Fig. 7C and D) with the \( X^* \) axis. Its length corresponds to the speed of flow. The mean speed is \( U_{XZ^*} \approx 3.3 \text{ m s}^{-1} \) \( (U_\infty = 2.24 \text{ m s}^{-1}) \) and \( U_{XZ^*} \approx 2.8 \text{ m s}^{-1} \) \( (U_\infty = 1.29 \text{ m s}^{-1}) \). Due to projection it is maximally ca 4.5% less than \( U_\infty \). The maximum values \( U_{XZ^*} \approx 7.1 \text{ m s}^{-1} \) \( (U_\infty = 2.24 \text{ m s}^{-1}) \) and \( U_{XZ^*} \approx 6.3 \text{ m s}^{-1} \) \( (U_\infty = 1.29 \text{ m s}^{-1}) \) are reached half way through upstroke. During both up- and downstroke a more or less constant angle of incidence is attained. The positive angle during down-and upstroke motion of the wing is distinctly smaller than the negative angle during upstroke. With increasing velocity of the free stream \( U_\infty \) the value of the angle decreases. A change from negative to positive values of the angle \( \tau_{XZ^*} \) occurs directly at the upper turning point only when there is no free stream \( U_\infty \) induced by fanning. Since the velocity \( U_\infty \) increases during the downstroke the angle \( \tau_{XZ^*} \) traverses zero. Contrary to this, the plus/minus sign change of the angle \( \tau_{XZ^*} \) at the lower turning point is independent of the free stream \( U_\infty \) induced by fanning.

The vector \( \vec{U}_{XY^*} \) (Fig. 8A and B) shows the velocity of flow to the chord and has the angle \( \tau_{XY^*} \) (Fig. 8C and D) to the \( X^* \) axis. This angle is called the aerodynamic sweep angle \( \gamma_{sweep}(t) \), because it characterises the components of the wing flow from the tip or from the joint. The mean velocity \( U_{XY^*} \) normal to the chord is approximately 53% \( (U_\infty = 0 \text{ m s}^{-1}) \) or 41% \( (U_\infty = 1.29 \text{ m s}^{-1}) \) or 33% \( (U_\infty = 2.24 \text{ m s}^{-1}) \) reduced. The aerodynamic sweep angle could not be taken into consideration when calculating quasi-stationary and non-stationary air forces.
2.3 The aerodynamic angle of attack

The aerodynamic angle of attack $\alpha_{\text{aero}}(t)$ is the angle between the flow $U_{XZ^*}$ and the chord: 
$\alpha_{\text{aero}}(t) = \tau_{XZ^*}(t) - \alpha_{\text{geom}}(t)$ (Fig. 9 sketch). Positive angles of attack signify flow against the lower surface; negative angles signify flow against the upper surface of the wing. With angles between $90^\circ$ and $-90^\circ$ flow comes from the front, between $90^\circ$ and $180^\circ$ or $-90^\circ$ and $-180^\circ$ flow comes from behind.

Due to the different flow parameters at the points P, LE and TE on the chord, different angles of attack $\alpha_{\text{aero}}$ (Fig. 9A), $\alpha_{\text{aero}} \text{LE}$ and $\alpha_{\text{aero}} \text{TE}$ (Fig. 9B) are calculated. The torsion of the wing
at the upper turning points could not be quantified. Thus only partially valid statements can be made on the aerodynamic angle of attack directly during turning.

During downstroke—once the wing has completed turning at the upper turning point—a positive angle of attack, without any great fluctuations, sets in at the leading edge point LE and at the section point P. The angle of attack is approximately $\alpha_{aero} = 20^\circ \ (U_\infty = 1.29 \text{ m s}^{-1})$, and decreases with increasing free stream.

At the lower turning point of wing movement the angle turns negative. Its value remains smaller than $90^\circ$, which means a constant flow from the front. The aerodynamic angle of attack first passes through zero at $\alpha_{aero \ LE}$ followed by $\alpha_{aero \ P}$ and finally at $\alpha_{aero \ TE}$. Thus flow to the leading edge
Figure 9: Aerodynamic angle of attack. A: two-dimensional calculation in the plane the chord moves (X*Z* plane in the wing reference system) B: angle of attack $\alpha_{\text{aero}}$ at P, fine line labels calculation with $U_\infty = 0 \text{ m s}^{-1}$, thick line labels calculation with $U_\infty = 1.29 \text{ m s}^{-1}$, dotted line labels calculation with $U_\infty = 2.24 \text{ m s}^{-1}$; C: angle of attack $\alpha_{\text{aero}}$ at LE and TE ($U_\infty = 1.29 \text{ m s}^{-1}$), dark grey line labels LE, light grey line labels TE.

of the wing comes from above, and to the trailing edge from below. The calculated flow direction can be correlated to the observed wing movement: the beginning of the upward movement of the leading edge leads to flow from above. At the same time the trailing edge moves with decreasing velocity downward and forward, so that flow attacks the lower surface. This flow results in the wing remaining spread out at the lower turning point. Ennos [7] also states that the influence of aerodynamic forces can stabilise the wings. From the data it is not possible to determine when the flow circulating around the wing changes direction or when a vortex is possibly shed.

During upstroke the aerodynamic angles of attack $\alpha_{\text{aero}}$ LE and $\alpha_{\text{aero}}$ P decrease continually until the value of the angle $\alpha_{\text{aero}}$ TE is reached. The angle $\alpha_{\text{aero}}$ TE changes only marginally after rotation at the lower turning point has been completed.

At the upper turning point the aerodynamic angle of attack enters the positive range again. Here, the plus/minus change in $\alpha_{\text{aero}}$ TE is distinctly retarded. The free stream $U_\infty$ at the upper turning point—contrary to the lower turning point—has a strong influence on the form in which the flow turns. Without free stream, the negative angle of attack increase at first to more than $-90^\circ$, i.e. the wing is attacked from behind. Since the flow direction continues to alter in this direction, but now from below, the calculated angle jumps from $-180^\circ$ to $+180^\circ$. Finally it sinks rapidly to less than $90^\circ$, since flow now comes from in front and below. Thus the flow at $U_\infty = 0$ has (formally) ‘turned once around the wing’ at the upper turning point. With a free stream of $U_\infty = 1.29$ or $2.24 \text{ m s}^{-1}$, the flow progresses different in principle: the aerodynamic angle of attack changes into the positive range by passing through the $0^\circ$ position. This means that the angle of flow from above, whilst continuing to flow from in front, turns to flow from below. The different flow directions
arise from the short, rapid sweep movement of the wing at the upper turning point. Without free stream \( U_\infty \) the wing is attacked from behind when it is pulled back. The flow from front is retained at the upper turning point only then, when the velocity of free stream is so high that it compensates or exceeds the flow induced by movement. The critical velocity \( U_\infty^{krit} \) necessary for this can be deducted from the velocity of the sweep movement: \( U_\infty^{krit} = 0.27 \, \text{m s}^{-1} \). It can be assumed that the change in flow at the upper turning point will result in shedding of the vortex. If the bees form a chain, a free stream of \( U_\infty > U_\infty^{krit} \) is already present at the beginning of movement.

The time delay of the aerodynamic angle of attack at the trailing edge, when passing through \( 0^\circ \) (or changing from \( \pm 180^\circ \) at \( U_\infty < U_\infty^{krit} \)), results in the leading edge being attacked from below whilst flow at the trailing edge still comes from above. Due to its construction, the wing forms a distinct arc when attacked by this flow. The distorted wing is distinctly visible on the video frame.

### 2.4 Measurement of air forces created during fanning

In order to evaluate the simulation results, the aerodynamic forces created during fanning were measured directly on the bees which stood on a small platform push into a recess in the landing platform. Unlike most ‘insect flight balances’ [8–10], the insects were not fixed. They held themselves to the landing platform by means of their claws.

The two aerodynamic force components—lift and thrust—were determined individually with different measuring systems. The platform was supported by two vertical double flexion springs, to which wire strain gauges were applied. The latter detected the thrust (resolution \( \approx \) 0.1 mN). Lift was determined by the analysing scales attached to the force-measuring platform (resolution \( \approx \) 0.01 mN). Only medium thrust and lift could be measured, because the system had high damping properties [5, 11, 12].

The mean thrust \( F_T \) of a single bee was \( F_T = 0.9 \, \text{mN} \) \((n = 22)\) (Fig. 10A). Thus it was nearly double as large as the mean lift \( F_L = 0.55 \, \text{mN} \) \((n = 27)\) (Fig. 10B). Relative to the body weight of a bee, mean thrust and lift were 81.2\% and 50.4\% respectively. Thus lift is distinctly lower than during flight when the animals have to compensate their own body weight. The resultant aerodynamic force was calculated by vector addition of the two components. The magnitude of vector amounts to 1.06 mN and the angle comes to 31.6\° to the horizontal line.

Occasionally, two bees stood very closely together on the measuring platform: they were fanning in a chain. In this case, since very little data with a large margin of error were available, only

![Figure 10: Measured aerodynamic forces. A: thrust \( F_T \), B: lift \( F_L \). Filled symbols label single fanning bees, open symbols label forces per bee when two bees are fanning on the platform.](image-url)
a tendency could be determined from the results. Thrust \((n = 4)\) lies within the range of single fanning bees. Lift \((n = 2)\), which is produced by each bee, is thus only approximately half as large. As a result, fanning animals should require much less energy to hold on to the underground.

### 3 Simulation of flow on the wings using a ‘mechanical bee’

For the mathematical simulation of non-stationary aerodynamics and evaluation of the results it was necessary to form as clear a picture as possible of the flow around the wings. Since it was not possible to render the flow visible on fanning bees itself, tests were carried out on a mechanical bee [13]. In order to reconstruct the non-stationary effects, the wings of the mechanical bee were built geometrically as similar as possible to real bees’ wings (scale 2:1). Beating and rotation movements of the wings imitated those of real fanning. The experiments were carried out using a beating frequency of \(f = 55\) Hz, which was approximately equivalent to half the frequency of fanning bees. Since the chord of the mechanical bee is twice as long, comparable Reynolds numbers were calculated. The mechanical bee was mounted on a narrow bar and the space below its wings was free, thus exclude the ground effect.

The flow was rendered visible by streams of smoke (Fig. 11) introduced at different positions into the flow sucked on by the mechanical bee. Single vortices and characteristic flow patterns on the wings were observed in high-speed registrations [5, 14]).

- Flow is sucked from in front.
- At the upper turning point a vortex forms on the leading edge.
- At the lower turning point a vortex forms on the leading edge.
- During downstroke a horizontal, spiral vortex forms on the upper surface close to the body.
- During upstroke a fluid is sucked on to the lower surface of the wing.
- The flow breaks away at the leading and trailing edges of the wing, but at no time does stall occur on the wing surface.

### 4 Simulation of the flow created during fanning and the calculation of the aerodynamic forces

The kinematic parameters of fanning, the measured flow velocity and the visualisation of flow on the mechanical bee indicate non-stationary flow on the wings. Especially within the range of the turning points, a fundamental change occurs in flow and wake. Similar observations in flying insects have been described [15–18].

![Figure 11: Mechanical Bee and examples of flow visualisation. The high speed pictures show two different positions of the wing beating in fanning mode (middle: downstroke, right: lower turning point/upstroke) with a frequency of \(f = 55\) Hz.](image)
Normally the reduced frequency \( K(K = (2\pi 0.5c)/\lambda = (\omega 0.5c)/U_{\infty}) \) is used when determining whether non-stationary flow is produced. The reduced frequency increases when the velocity of flow over the moving wing is faster than the velocity of free stream. Depending on the formulation chosen and the boundary conditions, with a value of \( K > 0.05 \) [19, 20] or \( K > 0.1 \) or \( K > 0.6 \) [21] non-stationary flow can be assumed. These limiting values only offer a rough orientation, since they relate to harmonic oscillations with small amplitudes and changes in the angles of attack. The mean reduced frequency of \( K_{\text{single}} = 0.69 \) or \( K_{\text{chain}} = 0.60 \), found in the analysed frames, is so high that a stationary flow can no longer be assumed.

The development of aerodynamic forces under non-stationary conditions can be described by three components: circulation, inertial and vortex components. The circulation component represents the influence of the bounded vortex. Since the wing not only moves itself, but also the surrounding fluid, it experiences a resistance which affects it like an added mass, the virtual mass [22]. This additional performance is found again as kinetic energy in the fluid. Part of the energy can be recovered if the wing reduces its speed of movement. This component is called the inertial component. The wake is varying under non-stationary conditions all the time. The influence of these changes on the development of aerodynamic forces is taken into consideration in the vortex component. In the ‘classical’ non-stationary theories this component is calculated from a weighted function that takes into account the influence of the wake (e.g. Theodorsen function). These functions cannot be applied here since they mostly presuppose small amplitudes of beating and rotation. The calculations were thus carried out using the Improved Method of Discrete Vortices (IMDV), which takes all three components into consideration (Fig. 12A).

### 4.1 The improved method of discrete vortices

Using IMDV, fluid movement is determined by following individual fluidic devices (Lagrange method). The fluidic elements are represented by discrete vortices. Since one is dealing with an non-stationary flow, the calculated flow parameters (velocity, pressure) and aerodynamic coefficients are dependent on time and point of calculation.

![Discrete vortices](image)

**Figure 12:** Discrete vortices. A: Bound discrete vortices on the chord show the effect of the bound circulation around the profile. B: Velocity of discrete vortices depends on the movement of the chord (no free stream present). C: Shed discrete vortices form the wake (shown for only one edge).
4.1.1 Notes to the calculation of the movement of fluid using IMDV

Simulation starts when wing movement in still air begins. As long as wing movement has not yet begun, all discrete vortices are bound to the chord (bound discrete vortices). During the first interval of calculation the circulation velocity $\Gamma_1$ of the bound discrete vortices is determined. Since there is not yet any free stream, velocity of flow attacking the chord is equal to the velocity of movement. The circulation of individual discrete vortices on the chord is just as fast as the velocity of fluid movement normal to the chord in this direction (Fig. 12B).

Taking the assumed fluid characteristics and the wing kinematics into consideration during simulation, discrete vortices are shed in each calculation interval with local flow velocity from the wing edges. These free discrete vortices move in the wake on the path of motion of fluid particles (Fig. 12C), and fulfil the Kutta condition. The clear physical pattern, created by their movement, is calculated from singular integral differential equations. These equations are based on the Cauchy motion equation. The adaptation of fundamental algorithms from the Method of Discrete Vortices [23, 24] for calculations from oscillating and rotating wings with two shedding edges was done in co-operation with A. Shekhovtsov, Institute of Hydromechanics, National Academy of Sciences of Ukraine [25, 26]. The convergent solutions of the singular integral differentiation equations are independent of boundary conditions such as the position of impenetrable wing surfaces, behaviour of discrete vortices at the edges of the simulation area, etc. By following the discrete vortices (according to the Helmholtz theorem), one can calculate the flow around a wing, flow descending into the wake, the process of rolling up to form (macro) vortices and the disintegration of the latter (for a further description of the IMDV application on fanning see Junge [5]).

4.1.1.1 Calculation of the velocity in fluid

Each discrete vortex induces a wing velocity field, and since they are restricted to a small area, the fields are frequently superposed. The velocity at one spot is thus dependent on the induced velocity of all bound and free discrete vortices [27] and is calculated using the additive Biot–Savart Law. The fact that a disturbance in a real fluid decreases with increasing distance from its source is approximated via linear function. Also the flow on the chord is superimposed by the velocity fields and influences the circulation of bound discrete vortices.

4.1.1.2 Calculation of pressure

The circulation, the velocity of movement and the direction of the discrete vortices are determined for each calculation interval. The pressure on the wing surface is dependent on these parameters. It is composed of the pressures from the circulation, inertial and vortex components. The circulation component is defined by the circulation along the outline, in which the bound discrete vortices are enclosed. Calculation of the pressure from the circulation of the vortices in the wake (vortex component) is dependent on the circulation and the position of the free discrete vortices. The inertial component depends on the virtual mass. This is acquired indirectly from the difference in the potential function between the upper and lower wing surfaces [26].

4.1.1.3 Calculation of the aerodynamic forces

The pressure acts normal to the upper surface of the wing. The integral of the difference in pressure between the upper and lower surfaces of a wing is the normal force. The coefficient of normal force is divided into lift and thrust coefficients.

4.1.2 Application of IMDV on the flow around the wings of fanning bees

Conditions/assumed simplifications:

- **Fluid:** The air is assumed to be infinite, continuous (ideal) and non-compressible. The temperature is constant.
• **Starting conditions in flow:** Simulation begins in still air: no vortex, no flow. Flow arising in a simulation is induced by the wing movement itself.
• **Flow descending into the wake:** The removal of the fluid (or rather the discrete vortices) from the wing occurs exclusively on the two edges of the wing. Separation of flow from the wing surface does not happen, thus fulfilling Kutta condition. It is now no longer suitable for calculating the circulation flow around a whole wing profile. The leading and trailing edges must be regarded separately.
• **Wing:** The wing profile is infinitely thin and flat. It is not deformed during wing beating nor penetrated by the fluid. Leading and trailing edges are sharp edges. The modelling is two-dimensional, so that an infinite stretching of the wing is assumed.
• **System of co-ordinates:** Only two-dimensional calculations could be carried out. But, in order to retain the original trajectory, a system of co-ordinates \((X', Y')\) was generated on the surface of a regular cylinder. The radius \(r\) is \(2/3\) of the wing length \(l\), the middle point is in the wing joint (Fig. 13). The co-ordinates of the chord are transformed in this system. The point of intersection \(P\) is on the surface of the cylinder only when the sweep angle is \(\gamma = 0°\). Since the sweep angle does not reach high values, there is very little distortion when projecting the points into the “cylindrical” system of co-ordinates.
• **Movement of the chord:** The simulation based on the co-ordinates of movement of the chord of an idealised wing beat (see Section 2.1). Wing beat begins with an upstroke from a horizontal position. The velocity was calculated from the transformed movement co-ordinates in the “cylindrical” system.
• **Simulating the second wing:** Only the movement of the fluid around one wing is calculated. The influence of the second wing is simulated by reflection onto the median plane. The interaction of flow around the wings is intense at the upper turning point. Due to the exact mirror-image behaviour of the wings, the generated vortices also progress as exact mirror images, and meet at the moment of penetrating the symmetry plane. Since the vortices rotate in opposing directions, and have the same intensity, they disintegrate.

### 4.1.3 Results from the simulation of flow in fanning wings

#### 4.1.3.1 Simulation of flow in a pair of fanning wings

The following presents the correlation between generated flow and created thrust—the most relevant aerodynamic component—during fanning. Thrust is calculated from the system of co-ordinates used, and contrary to lift, without distortion. The ground on which the fanning bees stand is not taken into account in this case.
**Upper turning point** (Fig. 14B and J; Fig. 15B and J; Fig. 16j and a) When approaching the upper turning point, wing movement slows down, and the effect of the inertia of mass becomes apparent. The fluid, thus set in motion, creates overpressure on the lower side of the wing. Due to the low negative angle of attack only small thrust values are calculated. The thrust increases due to the changing angle of attack when the wing begins to rotate.

**Downstroke** (Fig. 14C–G and K–O; Fig. 15C–G and K–O; Fig.16b–e) Separation of the wings at the upper turning point causes a strong negative pressure on their upper surface. Fluid is sucked over both wing edges onto the upper surfaces, and thrust reaches its maximum. The developing leading edge vortex increases rapidly and impedes further flow on the trailing edge. The inertia of mass of the fluid, which counteracts the acceleration of the wing, promotes the development of the leading edge vortex. At first, as a result of the angle of attack, relatively low positive thrust values are calculated. During the last third of downstroke the movement of the trailing edge increases more than that of the leading edge, thus increasing the intensity and expansion of the vortex. The coefficients of thrust increase distinctly. With the beginning of wing deceleration the effects of inertia appear again: the negative pressure on the upper surface declines. Since the angle of attack also decreases, thrust declines temporarily.

**Lower turning point** (Fig. 14H and P; Fig. 15H and P; Fig. 16f) As the wings continue to rotate, the negative pressure on the lower surface moves forwards, and thrust increases. The leading edge vortex, due to the rapidly changing angle of attack, remains attached to the wing upper surface, but moves towards the trailing edge. Thrust declines slightly with decreasing rotational speed.

**Upstroke** (Fig. 14A and I; Fig. 15A and I; Fig. 16g–i) The beginning of upstroke is accompanied by the dynamic delayed stall of the leading edge vortex. Flow directed to the rear and down develops. Due to the inertia of the added mass, wing acceleration leads to negative pressure, increased by the shed vortex on the lower wing surface. As a result of the large angle of attack high thrust values are calculated in this phase. Thrust declines only when acceleration decreases. A stable vortex, though possible as a result of the flow in the second half of upstroke, does not develop during upstroke. Vortex development is suppressed by the adjacent axis of symmetry.

By means of simulation with IMDV, a mean thrust of $F_T = 0.541 \text{ mN}$ was calculated. This corresponds to ca. 64% of the measured value. The thrust values are thus clearly higher than the results obtained from quasi-stationary calculations, but do not entirely explain the measured forces.

**4.1.3.2 Further simulations with altered boundary conditions** Further calculations were carried out to incorporate the influence of the ground. Although there was no principle difference in the course of thrust generation, it was shown that the system reacts very sensitively to changes in boundary conditions. The vortices shed close to the ground are limited in their diffusion, so that not only the flow near the ground is influenced, but also the distant fluid movements change. This is reflected in the production of a leading edge vortex during upstroke. This vortex strengthens the ‘flying’ effect at the upper turning point and weakens the leading edge vortex created during downstroke. A significant influence from the added mass was only found when the ground was very close to the lower turning point. The mean calculated thrust for simulation with ground was $F_T = 0.81 \text{ mN}$, and thus almost in the range of measured values.

Only a preliminary approach was made in simulating a fanning chain. Fanning wings were modelled with a distance of three chord lengths between each of them. To simplify matters since there was no information available on the phase shift in the beating cycle of a fanning chain, a synchronous movement was assumed. Thus the discrete vortices on different chords behave absolutely identically and the same pattern is generated in free discrete vortices. The proximity of the wing to each other prevents convection. In the calculation of several consecutive beating
Figure 14: Free discrete vortices shed in the wake. First beating circle after start in still air.
Figure 14: (Continued): Second beating circle after start in still air.
Figure 15: Calculated velocity vectors. First beating circle after start in still air.
Figure 15: (Continued): Second beating circle after start in still air.
cycles, the accumulation of discrete vortices leads increasingly to artefacts which make it more difficult to interpret the results. It was found, however, that also here only one vortex per beating cycle is shed and a clearly pronounced flow develops. The influence of the added mass on the generated aerodynamic forces decreases due to the stronger flow.

5 Discussion: Role of the coefficients of circulation, vortices and inertia in the development of aerodynamic forces during fanning

The kinematics of the wings and their flow determines the strength of the aerodynamically effective forces induced by inertia, circulation, and vortices. The velocity of wing movement is decisive in calculating the aerodynamic angle of attack, which in turn is decisive for the circulatory components. The added mass or the size of the force of inertia is determined by the acceleration of the wings. If the wing movement is approached by an harmonic oscillation \( \beta(t) = \beta_0 \sin(\omega t) \) then

\[
\dot{\beta} = \omega \sin \left( \omega t + \frac{\pi}{2} \right) \quad \text{and} \quad \ddot{\beta} = \omega^2 \sin (\omega t + \pi)
\]

is valid for the velocity and acceleration: The component of inertia thus increases proportional to the square of movement velocity, the circulation component proportional to movement velocity. An increase in movement velocity generally means only a slight increase in speed of free flow, it means the flow becomes more and more non-stationary. Thus, the proportion of inertial forces increases with increasing non-stationary flow. This is valid only as long as \( \text{Re} \gg 0 \); by \( \text{Re} \to 0 \), the influence of added mass can be ignored. The inertial component was calculated for fanning to contribute between 20\% and 30\%. An increase was also found with increasing reduced frequency.

Figure 16: Lift coefficient \( C_L \) and thrust coefficient \( C_T \) calculated with IMDV for fanning bees (without ground effect). Black line labels the angle \( \alpha' \), dotted line labels the velocity of movement in the \( X'Y' \)-system, dark grey line labels thrust coefficient \( C_T \), light grey line labels lift coefficient \( C_L \). Symbols: open arrow: effect of the added mass; curved arrow: vortex; +/-: pressure; dotted line: axis of symmetry.
The influence of circulation flow during fanning is greatly reduced due to velocity of flow and stall at both edges.

Calculations with IMDV revealed a correlation between the vortex component and the Reynolds number: if the development of the aerodynamic force is based mainly on the (inertial and) vortex component, as in fanning, the pressure on the wing surface rises with decreasing Reynolds numbers. With a pressure development dependent upon the (inertial and) circulatory component, the values increase with increasing Reynolds numbers. Contrary to (quasi-)stationary aerodynamic force generation, large angles of attack, as found here in fanning, are advantageous when forces are created by vortices. They enable the flow to stall and thus the vortices to develop on both wing edges ([18]: maximum lift at \( \alpha = 50^\circ \) or \( \alpha = 45^\circ \)). However, it is to suppress that the vortices drift too rapidly into the wake. Visualisation of flow on the mechanical bee has shown that, during fanning—as described in literature on flying insects or mechanical models [28, 29], the leading edge vortex expands radially, i.e. spirally along the longitudinal axis of the wing. This prevents rapid increase and shedding even at large angles of attack [30–32]. Radial acceleration develops from the negative pressure at the wing tip, which in turn, arises due to the increasing wing velocity along the longitudinal axis of the wing. A vortex, which induces flow to attack the wing so that the leading edge vortex is more strongly bound [33, 34], develops simultaneously at the wing tip due to the downward movement of the wing. Both the stabilisation in space of the leading edge, as well as the delayed stall due to rapidly changing angles of attack at the lower turning point, strengthen the vortex components [30, 35] and contribute to the, from a classical (quasi-stationary) aerodynamic point of view, inexplicably high aerodynamic forces. The ‘wake capture’ effect, discussed in literature [10], was not found in the fanning simulations and flow visualisation. Since it was not possible to take the radial fluid movement into consideration in the two-dimensional IMDV calculations, the pressure from the vortex component was underestimated. Furthermore, it was shown that shed vortices have a pronounced influence on the flow of a wing only as long as they are not more than one chord length removed.

6 Conclusion

The regular wing movements of fanning bees present a state of flight suitable for studying non-stationary aerodynamic effects. IMDV was applied for non-stationary calculations on the basis of the three-dimensional kinematic data and the measured airflow produced by fanning. With this method it was possible to model the non-stationary airflow around the virtual oscillating wing (two-dimensional), the wake and the resulting aerodynamic forces. Measured aerodynamic forces as well as the produced lift and thrust allow an assessment of the model calculations. The results correspond satisfactory. Based on the simulated vortex pattern and the way the lines of equal pressure and velocities develop it was possible to analyse the effect of inertia, the influence of the wake and the circulation around the wing. The proportion of these three components supports the hypothesis that fanning bees generate the aerodynamic forces based on the inertial and vortical principles.

Acknowledgements

This research was founded by Deutsche Forschungsgemeinschaft (DFG) and University of Saarland Dep. Zoology. Also thanks to Prof. W. Nachtigall for supervising this work.
Nomenclature

$c$  m  chord of the wing (see Fig. 2)
$C_T, C_L$ –  thrust coefficient, lift coefficient
$F$  mN  force
$F_L$  mN  lift force
$F_T$  mN  thrust force
$f$  Hz  frequency
$G$  –  wing joint (see Fig. 2)
$K$  –  reduced frequency $K = (2\pi 0.5c)/\lambda = (\omega 0.5c)/U_\infty$
$l$  m  length of the wing (see Fig. 2)
$LE$  –  leading edge point (see Fig. 2)
$n$  –  number
$P$  –  point of intersection of chord $c$ and longitudinal axis $l$ (see Fig. 2)
$r$  m  radius
$R$  –  Reynolds number
$t$  s  time
$TE$  –  trailing edge point (see Fig. 2)
$S$  –  wing tip (see Fig. 2)
$u$  m/s  velocity/speed of the wing (see Fig. 6)
$U$  m/s  velocity/speed (component) of the effective flow (see Fig. 6)
$U_\infty$  m/s  velocity/speed of free stream (see Fig. 6)
$X, Y, Z$  m  axes of the Cartesian system of coordinates (see Fig. 2)
$x, y, z$  m  Cartesian coordinates
$X^*, Y^*, Z^*$  m  axes of the wing reference system (see Fig. 7)
$x^*, y^*, z^*$  m  coordinates in the wing reference system
$X', Y'$  m  axes of the system of coordinates on the surface of a cylinder
  (see Fig. 13)
$x', y'$  m  coordinates on the surface of a cylinder
$\alpha$  deg  angle of attack (see Fig. 9)
$\beta$  deg  flapping angle (see Fig. 3)
$\Gamma$  m$^2$/s  circulation
$\gamma$  deg  sweep angle (see Fig. 4)
$\lambda$  m  wavelength
$\mu$  deg  angle of inclination of the trajectory (see Fig. 2)
$\tau$  deg  angle (components of the effective flow) (see Figs 7 and 8)
$\chi$  deg  phase difference
$\omega$  l/s  circular frequency (angular velocity) of oscillation

References


