Chapter 2

Using miniature sensor coils for simultaneous measurement of orientation and position of small, fast-moving animals

SUMMARY

A system is described that measures, with a sampling frequency of 1 kHz, the orientation and position of a blowfly (*Calliphora vicina*) flying in a volume of $0.4 \times 0.4 \times 0.4\ m^3$. Orientation is measured with a typical accuracy of $0.5^\circ$, and position with a typical accuracy of 1 mm. This is accomplished by producing a time-varying magnetic field with three orthogonal pairs of field coils, driven sinusoidally at frequencies of 50, 68, and 86 kHz, respectively. Each pair induces a voltage at the corresponding frequency in each of three miniature orthogonal sensor coils mounted on the animal. The sensor coils are connected via thin (12 µm) wires to a set of 9 lock-in amplifiers, each locking to one of the three field frequencies. Two of the pairs of field coils produce approximately homogeneous magnetic fields, which are necessary for reconstructing the orientation of the animal. The third pair produces a gradient field, which is necessary for reconstructing the position of the animal. Both sensor coils and leads are light enough (0.8-1.6 mg for three sensor coils of 40-80 windings, and 6.7 mg/m for the leads, causing a maximal load of approximately 5.7 mg) not to hinder normal flight of the animal (typical weight 80 mg). In general, the system can be used for high-speed recordings of head, eye or limb movements, where a wire connection is possible, but the mechanical load on the moving parts needs to be very small.

INTRODUCTION

In behavioural research it is often necessary to measure both the position and the orientation of moving animals, or of parts of their body, such as limbs or eyes. If the animal is fairly large and moves relatively slowly, video techniques are most convenient (e.g., Sandström *et al.*, 1996). But if the animal is small and moves in a

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relatively large space, the typical spatial resolution of a video system may not be high enough to obtain a good estimate of the orientation. Moreover, the frame rate of conventional video systems may be too low for accurately monitoring details of the movement if the animal moves fast. We encountered such a situation when we embarked on a study of insect flight, with the purpose to reconstruct the dynamic visual stimulus and the optic flow (i.e., the field of local movements of the visual stimulus) as seen by the insect’s visual system during flight. The blowflies used in this study (*Calliphora vicina*) move at a speed of up to 1 m/s in a restricted space (a cage of 0.4×0.4×0.4 m³, with a visual scene covering the walls), and make very fast turns of up to several thousand degree/s (for measurements in related species see Wagner, 1986; Land and Collett, 1974; Collett and Land, 1975; Land, 1993).

The temporal and angular resolution of blowfly photoreceptors are in the order of 7 ms and 1.5°, respectively (full width at half maximum, see, e.g., van Hateren, 1992; Smakman *et al*., 1984). For an accurate reconstruction of the visual input, the temporal and angular resolution of the monitoring system recording how the head moves during flight needs to be a few times better than these values. There is also a constraint on the spatial resolution, because it is related to the angular resolution: a positional error of 1 mm causes an error in orientation of up to 1° when a visual target is viewed from a distance of 6 cm (in a direction orthogonal to the direction of the positional error; in other directions the error is smaller). With this distance as a reasonable lower limit during flight, the resulting specifications for the monitoring system are a resolution of at least 2 ms in time, 0.5° in orientation (for each of three orientational angles), and 1 mm in position (for each of three spatial axes). This is beyond the capabilities of a conventional video system. Therefore, we decided to develop an alternative method that does meet the requirements. It is a variation on the well-known search coil technique for measuring eye and head movements (see e.g., Ferman *et al*., 1987; Kasper *et al*., 1987; Hess, 1990; and Schwenne and Zarnack, 1987, where it is applied to measuring wing movements in locust). In addition to giving the orientation of the sensor coils, as in earlier methods, our system also gives their position.

**SYSTEM DESCRIPTION**

*Principle of operation*

Figure 1 shows a scheme of the setup. Sinusoidal currents, with frequencies of 50, 68, and 86 kHz, flow through three orthogonal pairs of field coils. For two of these pairs, current flows in the same direction through each coil of the pair. As a result, the two magnetic fields are roughly homogeneous in the volume enclosed by the coils (Fig. 2A shows one of these fields). For the third pair, current flows in opposite directions through the two coils. As a result, the magnetic field is zero at the midpoint between the coils (see Fig. 2B), and pointing into opposite directions close to the centers of the two coils. This gradient in the field occurs not only along the
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axis of symmetry connecting the centers of the coils (in Fig. 2B a vertical axis at the center of the figure), but also along any perpendicular axis through the midpoint between the coils (e.g., in Fig. 2B a horizontal axis at the center of the figure; see also Fig. 1, broken arrows in the lower left diagram). This means that each point in the volume has a unique magnetic field vector, i.e., with a unique combination of magnitude and direction. Therefore, an accurate measurement of the magnetic field vector produced by this third pair of coils will give the position within the measurement volume.

The time-varying magnetic field, produced by the superposition of the two homogeneous fields and the gradient field, induces voltages in three small orthogonal sensor coils (Fig. 3, inset). These sensor coils are each connected to three lock-in amplifiers, each tuned to one of the three frequencies present in the magnetic field. Thus a total of 9 lock-in amplifiers yield 9 parameters, from which the 6 parameters describing the orientation and position of the sensor coils can be extracted. This is possible, because the two homogeneous fields induce voltages in the sensor coils primarily related to their orientation, whereas the gradient field induces voltages in the sensor coils primarily related to their position. Two orthogonal sensor coils would suffice to determine orientation in the presence of two orthogonal homogeneous magnetic fields, but a third coil is necessary for determining the position using the gradient field. With three sensor coils, all three
components of the gradient field vector can be measured, which then uniquely determines the position. The third sensor coil also enables measurement of orientation at positions in the volume where the homogeneous fields deviate from homogeneity. The algorithm used for extracting the orientation and position from the measured parameters is described below in the section Calibration and reconstruction.

Manufacturing the sensor coils

In order not to disturb the normal movement of those body parts under investigation, the weight of the sensor coils and of the connecting leads need to be much smaller than the weight of these body parts. Therefore, we use thin wire of 12 µm diameter (with two layers of insulation, 1 µm polyurethane and 1 µm polyvinylbutyral; Lotan-Fix, Huber & Suhner AG, Switzerland). The coils are produced by winding the wire around a hollow axis of flexible material (Teflon; see Fig. 3 for the device used for winding coils). Before winding, a thin metal expansion rod is inserted into the hollow axis; the fit is such that this slightly increases the diameter of the axis. Approximately 1 m of wire, later used for connecting the coil, is first wound on a storage reel. Subsequently, the coil is wound, and glued together by slightly heating the outer layer of the wire insulation. Removal of the metal rod loosens the coil from the axis, after which it can be shifted from the axis with the help of a tightly fitting glider (see Fig. 3). To prevent breaking of the wire, a tension loosener loosens the wire before the coil is shifted from the axis. Finally, the wire is unwound from the
storage reel, and twisted, by means of a motor, with the other wire originating from the coil. The tension during the twisting is controlled by hanging small weights at the end of each wire (see Koch, 1980). Careful twisting is essential to prevent induction of voltage in the resulting leads.

With the technique described above, we are able to make coils as small as 0.8 mm in diameter, but for most experiments we used coils of 2 mm diameter, with 40 or 80 windings. This gives a good compromise between weight (0.8-1.6 mg for the three coils) and signal-to-noise ratio: the larger the diameter of the coils, and the more windings they have, the larger the signal that is induced and the better the signal-to-noise ratio. Coils of 2 mm diameter and 40 windings are light enough for mounting on either the head or the thorax of a blowfly (the typical weight of the head is only 8 mg, whereas the entire blowfly weighs typically 80 mg). Figure 3 (inset) shows the resulting system of three coils. These were made with slightly different diameters (2.0, 2.1, and 2.2 mm) such that they fit within each other. The coils are fitted together as orthogonally as possible using a template with orthogonal grooves. In the calibration procedure (see below) their exact relative orientations are measured, and these actual orientations are used in the calculations performed for reconstructing the orientation and position of the blowfly.

Magnetic fields and lock-in amplifiers

The square field coils (with sides of 45 cm) are driven by power amplifiers (SMOS248, ILP Electronics Ltd., Canterbury, UK) with as source signal the output of the sine generators of three of the lock-in amplifiers. In order to increase the current through the coils (and thus the magnitude of the magnetic field and the voltage in the sensor coils), combinations of capacitors (polypropylene, total capacitance 7.2 nF, 3.7 nF, and 2.5 nF for frequencies 50 kHz, 68 kHz, and 86 kHz, respectively) are inserted in series with the coils, such that each circuit has a resonance frequency close to the driving frequency. As a result, the current through each of the field coils is approximately 3 A (peak-peak). With 25 windings, this results in a magnetic field of 0.15 mT (peak-peak) at the midpoint between the coils that produce a homogeneous field. The square windings of the field coils are made...
of 1.9 mm copper wire, at a distance (center-center) of 5 mm from each other in order to reduce the proximity effect (Terman, 1943). To reduce electrical coupling from the field coils to the sensor coils and their leads (see e.g., Koch, 1980), the field coils are electrically shielded with a grounded fine mesh (which avoids significant eddy currents).

The sensor coils are connected to lock-in amplifiers (LIA-F-140, with a customized range of time-constants, Femto Messtechnik, Berlin, Germany). The lock-in amplifiers are in differential mode, which makes it possible to further reduce electrical coupling from the field coils to the leads by balancing the input impedances of the two inputs (by using a fixed resistor of 250 $\Omega$ in series with one lead of a sensor coil, and an adjustable resistor of 0-500 $\Omega$ in series with the other lead). The time-constant of the lock-in amplifiers was set at 1 ms (with the slope of the low-pass filter at 40 dB/dec), and their output was digitized by a 16-bit A/D-converter (Microstar DAP2416e, driven by Dasylab) at a sampling rate of 1 kHz, and stored on disk for off-line analysis.

Calibration and reconstruction

Although it is in principle possible to calculate the magnetic field from the configuration of the currents, the multiple windings in the field coils and the elaborate shielding makes this a complicated procedure. Therefore, we measured the magnetic fields directly. As the coils consist mainly of long straight wires carrying the current, it follows from the Biot-Savart law that the curvature of the magnetic field is in good approximation inversely related to the distance to the closest current. By keeping a (small) distance between the wall of the cage and the coils, there is a maximum to the curvature of the magnetic field within the measurement volume. This means that the magnetic field as a function of position is a band-limited signal. From the sampling theorem it then follows that the magnetic field at any point is completely determined by its values at a limited number of sampling points. For measuring the field at such a set of points, we constructed a set of three calibration coils, which were made orthogonal (within 0.3°) by winding them in grooves made on a cube of 1×1×1 cm$^3$. When this set of coils is aligned with the coordinate system (defined by the orientation of the field coils), the output of each of these coils at a particular frequency is proportional to the amplitude of one component of the magnetic field vector at that frequency (i.e., due to a particular pair of field coils). Thus the 9 lock-in amplifiers give directly the 3×3 vector components of the magnetic fields produced by the three pairs of field coils. Measurements were made with the calibration coils at 7×7×7 positions evenly spaced throughout the measurement volume. Finally, for each magnetic field, the vector components were calculated on a 100×100×100 lattice, where components at intermediate positions between the 7×7×7 measured points were determined by cubic spline interpolation per component (using routines spline and splint from Press et al., 1992). The 9 resulting sets of 100×100×100 magnetic field components were stored, and used
during the reconstruction to give, by linear interpolation, the magnetic field at any position.

The sensor coils (e.g., Fig. 3, inset) are made approximately orthogonal, but usually not exactly. In order to correct for any deviations from orthogonality, the system of three sensor coils was calibrated (see below). This calibration yields a 3x3 matrix that contains the exact orientation of each sensor coil, and its gain (which depends on the area and number of windings of that coil). From the calibration of the magnetic field and the sensor coils, a forward model was constructed. This model predicts the output of the lock-in amplifiers as a function of the orientation and position of the sensor coils. This gives

\[
\begin{bmatrix}
L_{a1}(r, \theta, \varphi, \psi) & L_{a2}(r, \theta, \varphi, \psi) & L_{a3}(r, \theta, \varphi, \psi) \\
L_{b1}(r, \theta, \varphi, \psi) & L_{b2}(r, \theta, \varphi, \psi) & L_{b3}(r, \theta, \varphi, \psi) \\
L_{c1}(r, \theta, \varphi, \psi) & L_{c2}(r, \theta, \varphi, \psi) & L_{c3}(r, \theta, \varphi, \psi)
\end{bmatrix}
= \begin{bmatrix}
C_{\alpha x} & C_{\alpha y} & C_{\alpha z} \\
C_{\beta x} & C_{\beta y} & C_{\beta z} \\
C_{\gamma x} & C_{\gamma y} & C_{\gamma z}
\end{bmatrix}
\begin{bmatrix}
\cos \theta \cos \varphi & \sin \theta \cos \varphi & -\sin \varphi \\
\cos \varphi \sin \psi - \sin \theta \cos \psi & \sin \theta \sin \varphi \sin \psi + \cos \theta \cos \psi & \cos \varphi \sin \psi \\
\cos \varphi \sin \psi + \sin \theta \sin \varphi \sin \psi & \sin \theta \sin \varphi \cos \psi - \cos \theta \sin \psi & \cos \varphi \cos \psi
\end{bmatrix}
\begin{bmatrix}
B_{1x}(r) & B_{1y}(r) & B_{1z}(r) \\
B_{2x}(r) & B_{2y}(r) & B_{2z}(r) \\
B_{3x}(r) & B_{3y}(r) & B_{3z}(r)
\end{bmatrix}
\]

where \(L_{a1}(r, \theta, \varphi, \psi)\) is the output of the lock-in amplifier connected to the sensor coil \(\alpha\) and tuned to the frequency of field coil pair 1, with the sensor coils at a position \(r\) and an orientation \((\theta, \varphi, \psi)\) in the measurement volume. The (row) elements \((C_{\alpha x}, C_{\alpha y}, C_{\alpha z})\) form the normal vector of sensor coil \(\alpha\) when the three sensor coils are in their reference orientation, multiplied by the gain of sensor coil \(\alpha\). In practice, the (column) elements \((C_{\alpha x}, C_{\beta x}, C_{\gamma x})\) are measured directly as the outputs of the lock-in amplifiers tuned to field 1 and connected to sensor coils \(\alpha\), \(\beta\), and \(\gamma\) when sensor coil \(\alpha\) is approximately aligned with field 1 during the calibration of the sensor coils. Similarly, \((C_{\alpha y}, C_{\beta y}, C_{\gamma y})\) and \((C_{\alpha z}, C_{\beta z}, C_{\gamma z})\) are obtained for two other orthogonal orientations of the sensor coils with field 1 (approximately aligned with sensor coils \(\beta\) and \(\gamma\), respectively). The middle matrix on the right side of Equation (1) is a rotation matrix in the Fick gimbal system (e.g., Haslwanter, 1995), with \(\theta\) the yaw (rotation around the vertical axis), \(\varphi\) the pitch (rotation around the horizontal axis perpendicular to the length axis of the animal), and \(\psi\) the roll (rotation around the length axis). Finally, \(B_{1x}(\vec{r})\) is proportional to the \(x\)-component of the magnetic field due to field coils 1, at a position \(\vec{r}\). In practice, this matrix element is measured during the field calibration as the output of the lock-in amplifier tuned to field 1 and connected to the calibration coil oriented in the \(x\)-
direction, divided by the gain of this calibration coil (determined from the output obtained when it is mounted at the center of a homogeneous field, with the plane of the coil orthogonal to the field). In separate experiments we checked and verified the forward model of Equation (1).

If we denote the set of 9 outputs \( L_{a1}(r^x, \theta, \phi, \psi) \ldots L_{a3}(r^x, \theta, \phi, \psi) \) by a vector \( \mathbf{L}(r^x, \theta, \phi, \psi) \), the purpose of the reconstruction algorithm is to find those values of \( r^x, \theta, \phi, \) and \( \psi \) (i.e., 6 parameters) that minimize the difference (in the least-squares sense) between the predicted \( \mathbf{L}^{\text{predicted}} \) and the measured \( \mathbf{L}^{\text{measured}} \). This minimization is performed by a least-squares routine (amoeba, from Press et al. 1992), that gives

\[
\min_{r^x, \theta, \phi, \psi} \left\| \mathbf{L}^{\text{predicted}} - \mathbf{L}^{\text{measured}} \right\|^2 = \\
\min_{r^x, \theta, \phi, \psi} \sum_{i=1,2,3} \left( L_{i,j,\text{predicted}}(r^x, \theta, \phi, \psi) - L_{i,j,\text{measured}}(r^x, \theta, \phi, \psi) \right)^2.
\]

This yields an estimate of the position \( r^x \) and orientation \( (\theta, \phi, \psi) \) at each time where a measurement was taken. This calculation takes about 4 ms per measured point on a fast workstation (HP J280), which means that with a sampling rate of 1 kHz (1 ms per measurement) the reconstruction can be done within a reasonable time, only about 4 times longer than the experiment itself. It is probably possible to obtain better than real-time performance (thus enabling on-line reconstruction) by using a neural network trained to perform the reconstruction.

**Accuracy**

By moving the set of three sensor coils repeatedly along a known trajectory at various positions within the measurement volume, we estimated the systematic and random (stochastic) errors of the system (see Fig. 4A for an example). Systematic errors are important if an absolute reconstruction of the viewing direction and position is required. Random errors are important for relative variations of viewing direction, e.g., as needed for the angular speed of gaze shifts. Due to the shape of the fields (see Fig. 2), the errors in the position and orientation depend on the distance from the center of the measurement volume. We found systematic errors (primarily due to small errors in the field calibration) for the orientational angles of 0.2° and 0.3° (for sensor coils with 80 and 40 windings, respectively) in the central half of the measurement volume (i.e., a central cube with 30 cm sides), gradually rising to 0.7° and 1° (80 and 40 windings) in the corners of the measurement volume. Random errors (standard deviations) in orientational angles were 0.15° and 0.3° (80 and 40 windings) in the central volume, up to 0.3° and 0.5° in the corners. Systematic errors in the position were 1.5 mm and 2 mm (80 and 40 windings) in the central volume, up to 3 mm and 5 mm (80 and 40 windings) in the corners; random errors in the
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position were 0.5 mm and 0.7 mm (80 and 40 windings) in the central volume, up to 0.7 mm and 1 mm (80 and 40 windings) in the corners.

The random errors can be reduced by using magnetic fields that are stronger or have a higher frequency, by increasing the diameter or the number of windings of the sensor coils, or by improving the signal-to-noise ratio of the electronics. In our system, the total resistance of sensor coils, leads and balancing resistances is approximately 1 kΩ, and the lock-in amplifiers are measuring voltage. If this resistance is reduced (e.g., with shorter leads, or wire of larger diameter), the signal-to-noise ratio will become better by using lock-in amplifiers that measure current, or by using a specialized system like that designed and manufactured by Remmel (1984).

The systematic errors arise mainly from small errors in the calibration of the magnetic field, mostly due to the interpolation. These errors can be reduced by increasing the number of points where the field is measured. Another potential improvement is the use of a better interpolation procedure than cubic spline interpolation. As the magnetic fields are relatively slowly varying in time, the differential equation to which they obey is fairly simple (the Laplace equation for the magnetic scalar potential, see Jackson, 1975). It may thus be quite feasible to use this extra information about the shape of the magnetic fields to improve the estimate of the magnetic field, both at and between the measured points.

![Figure 4](image-url) (A) Traces recorded whilst moving the sensor coils, by hand, along a guiding rail in the y-direction. The small, systematic variations in the other coordinates (x, z, θ, ϕ, and ψ) are absolute errors due to small deviations in the field calibration. The noise in the traces (arising from noise in the electronics) gives an impression of the precision (i.e., random errors) of the system. (B) Example of a flight path, recorded from the thorax of a flying blowfly. The three-dimensional path (in this case almost confined to a horizontal plane) was projected on a horizontal plane. Dots show positions at consecutive ms (starting at ms 0, ending at ms 1000), the arrows the orientation of the thorax at 20 ms intervals.
APPLICATION

A set of three sensor coils of 2 mm diameter each, consisting of 80 windings, was attached to the thorax of a blowfly. The leads were led to the abdomen, and, via a free stretch of approximately 80 cm, to the bottom of the cage, and finally to the lock-in amplifiers. Total weight of coils and leads (approximately 7 mg) was much smaller than the weight of a blowfly (typically 80 mg). The coils and leads did not appear to hinder normal free flight, which was checked by comparing flight performance with different weights of the coils and leads. The walls of the cage were covered with transparencies onto which a natural image (primarily foliage) was printed. The walls were illuminated from the outside through frosted paper.

Figure 4B shows an example of a horizontal projection of a reconstructed flight path. The total duration of the stretch shown is 1 s, with the dots denoting the position at 1 ms intervals. The arrows show the orientation of the thorax, shown only at 20 ms intervals for the sake of clarity. As can be seen in the figure, turns by the thorax can be very fast (e.g., a turn of more than 60° in 40 ms at time 100 ms), and the orientation of the thorax is more involved in the dynamics of turning than in aligning with the direction of forward motion.

CONCLUSION

The system described here solves the problem we were faced with: measuring, with sufficient accuracy, the orientation and position of a small, fast-moving animal. By reducing the time constants of the lock-in amplifiers, the system can be adjusted for even faster movements (although this would increase the noise in the output, and thus reduce the orientational and spatial resolution). Alternatively, if it is possible to use heavier sensor coils, the accuracy of the system can be improved appreciably by increasing the diameter or number of windings of the sensor coils. This flexibility makes the system well suited for a range of applications in behavioural research.

REFERENCES


Chapter 2


**APPENDIX: TECHNICAL DETAILS**

*Field coils*

For obtaining a signal of several millivolts rms in the sensor coils, oscillating magnetic fields with a strength of approximately 100 A/m p-p (peak-to-peak) are needed, which is equivalent to 0.13 mT. Frequencies of about 70 kHz must be created (see below). The field strength in the midpoint between two circular coils placed at a distance equal to their diameter \(d\), having \(N\) windings and carrying a current \(I\) is given by \(0.7NI d^{-2}\) (Jiles, 1991). Assuming a coil diameter of approximately 0.5 m and a current of 3 A p-p this implies that the coil must have about 25 windings. The self inductance \(L\) of a square coil with a square cross section is approximately (Terman, 1943):

\[
L = \frac{1}{2} \mu_0 D N^2 \left[ \ln \left( \frac{5.67 D d_w^{-1} N^{-1/2}}{1.68} \right) \right] \text{ (H)}
\]

where \(D\) is the length of a side of the coil, \(N\) the number of windings and \(d_w\) the diameter of the wire used. With \(d_w = 1.9\) mm, \(D = 0.5\) m and \(N = 25\), \(L\) is approximately 1 mH.

It is not trivial to produce magnetic fields at frequencies around 70 kHz with field strengths of about 100 A/m p-p. Two effects occur at these frequencies which can raise the resistance in a coil dramatically: the well-known skin effect and the proximity effect. The increase in resistance depends on the frequency of the current, the coil diameter, the wire diameter, the distance between the wires, the number of windings and the number of layers. The resistance was determined from simulations by a commercially available software package (Maxwell 2D Field Simulator 6.3, Ansoft), testing a range of values for the parameters mentioned above. Further complications arise from the internal capacity of the coil. This capacity is connected in parallel with the coil in the equivalent scheme, and thus increases the impedance (see below). Formulas found in the literature only give an estimate of the magnitude of this capacity (Terman, 1943; Zinke, 1965). These estimates were taken into account in the final calculation of the field strength. A reasonable compromise between maximum field strength and practical limitations is a square coil having sides of 0.5 m, 25 copper windings with a \(d_w\) of 1.9 mm, a center to center wire distance of 5 mm and consisting of 5 layers, each consisting of 5 windings.

*LC circuit*

The impedance of a coil with \(L = 1\) mH and \(R = 6\) \(\Omega\) at 70 kHz is dominated by the factor \(\omega L\), which is approximately 450 \(\Omega\). Directly driving this coil with \(I = 3\) A p-p
then requires a source with a voltage of 1350 V p-p. As such a source is not practical, either the current can be reduced (a) or the voltage (b).

In (a), a tuned capacitor is connected in parallel with the coil (see Fig. 5A), raising the impedance to about 40 kΩ. In that case the source would still have to deliver 1350 V, just as when it would be connected to the coil only, nevertheless, the current the source would have to deliver is reduced to 0.03 A.

In (b) a tuned capacitor is connected in series with the coil (see Fig. 5B). The resulting impedance of the LC circuit drops to a value equal to the resistance in the LC circuit (the sum of the resistance of the coil, the internal resistance in the capacitor and in conductors in the surroundings of the coil). The capacitor should be tuned according to $\omega = (LC)^{-\frac{1}{2}}$. A current of 3 A p-p will thus be flowing through the 6 Ω circuit, while the source has to deliver a voltage of only 18 V p-p, instead of 1350 V. The voltage over the coil will still be 1350 V due to the resonance in the circuit. The power delivered by the source is the same in both (a) and (b). Since regular power amplifiers are able to produce several amperes while the voltage output is often limited to a value of about 100 V p-p, the series resonant circuit (b) is the most suitable solution.

**Capacitors**

The capacitor used for the LC circuit must be able to withstand a high voltage (see above). Furthermore, the internal resistance must be as low as possible to avoid a significant rise of the resistance of the LC circuit and a possible heat problem. For a capacitor with capacitance $C$ and resistance $R$, the series resistance in a capacitor is determined by $\tan(\delta) = R\omega C$, with $\delta$ the angle between the complex impedance of the capacitor and the imaginary axis. $\tan(\delta)$ is also called the power factor and is zero in the ideal capacitor. In real capacitors it is not, and its magnitude is material dependent. Polypropylene capacitors have a low power factor of $10^{-3}$ or smaller (Zinke), are easily available and are therefore used in the circuit. The capacitance needed for the three LC circuits is 7.2, 3.7 and 2.5 nF for frequencies of 50, 68 and 86 kHz, respectively. With the smallest product of $\omega C$ being $1.35 \times 10^{-3}$ Ω$^{-1}$, the value of $R$ is maximally 0.74 Ω. This is low compared to the resistance of the field coils (see above) while the heat production ($R I_{RMS}^2$) is limited to an acceptable
maximum of 0.8 W. Since a single capacitor can not withstand the high voltage that is created in the LC circuit a series circuit of mainly 33 nF capacitors is used (the individual capacitors have lower internal resistances but the total resistance remains the same).

**Coil drivers**

The three coil drivers each contain a power supply (+/– 40 Volt), a commercially available power amplifier (SMOS248, ILP Electronics Ltd., Canterbury, UK), and a feedback circuit which improves the stability of the current flowing through the field coils. The latter measures the voltage over a resistance bridge made of constantane which is connected in series with the LC circuit. The voltage over the bridge is a measure for the current flowing through the LC circuit, and is used as input to the feedback circuit. Input to the coil drivers comes from the sine generators of three of the lock-in amplifiers with frequencies of 50, 68 and 86 kHz. The stability of the magnetic fields was measured with the aid of a sensor coil and a digital lock-in amplifier (SRS 850). Long term fluctuations in magnetic field strength were less than 2-3‰.

**Coil shielding**

The potential of the field coils is inevitably coupled to the leads via stray capacitance; this causes an extra signal measured by the lock-in amplifiers. When one lead is connected to earth and the other one to a lock-in amplifier, it can be shown from an equivalent circuit (see Fig. 6) that the extra signal has an amplitude $V_S$ given by $V_S = V_{coil} R_L Z_C^{-1}$, in which $V_{coil}$ is the voltage over the field coil, $R_L$ the resistance of the lead and $Z_C$ the impedance of the capacitance between field coil and lead. To obtain an order of magnitude of $V_C$ take $R_L$ to be about 500 $\Omega$, $V_{coil}$ about 1000 V, and the capacity between the field coil and the leads of the sensor coils about 10 pF (Terman, 1943). This gives a $Z_C$ of about $0.2 \times 10^6 \Omega$ at 70 kHz. Then $V_S$ is of the order of 2 V (which is actually observed), which is much higher than the magnetically induced signal which has to be measured (2-5 mV). To reduce this extra signal an electrical shielding, connected to earth, is placed around each of the field coils. It consists of 4 pieces of 2 m long aluminum tape sticked onto the housing of the field coil. Each piece is cut into strips along the length of the tape of around 0.5 cm width (to avoid significant eddy currents). The strips were still connected to each other because one end of the tape was not cut over a distance of one centimeter. Though the capacitive coupling was effectively ruled out, there still remained a voltage of about 5 V on the electrical shielding, caused by magnetic induction. To prevent influence of this voltage, via stray capacitance, on the signals to be measured, other measures have to be taken (see below). A side-effect of the electrical shielding is an extra capacitance it causes between a coil and the earth. This increases the impedance because it is in fact connected in parallel with the coil.
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Sensor coil signals

The maximum rms voltages induced by the homogeneous magnetic fields in the sensor coils with 80 windings and 2 mm diameter are dependent on position and orientation, and range from 2-5 mV. The leads are soldered onto 1 cm long copper pins which are plugged into a connector. These connections are double shielded by two aluminum boxes (see Fig. 7). The signals are transmitted by double shielded, twisted cables to a double shielded aluminum box in which the signals are split into 18 cables which run to the nine lock-in amplifiers. Another set of nine lock-in amplifiers was used when flies carried sensor coils on both head and thorax.

Impedance correction circuit

To reduce the influence of the voltage from the electrical shielding the lock-in amplifiers must be used in differential mode. This cancels the capacitive voltages in each of the leads. Since the input impedances of the lock-in amplifiers are not exactly equal, and thus cause some remaining voltage, a correction circuit as shown in Fig. 8 was added. For the adjustment of the correction circuit a test cable is used, consisting of two twisted 12 µm leads with directly connected ends instead of a

Figure 6. Equivalent circuit with the stray capacitance $C$ between the field coil, which carries a voltage $V_{coil}$, and the leads of the sensor coil. $V_{ind}$ is the magnetically induced voltage over the sensor coil. $R_L$ is the resistance of a lead.

Figure 7. Circuit measuring the sensor coil signals. Stippled lines indicate wires carrying signals, dashed lines indicate ground. Fat lines indicate shieldings (cable mantles and boxes). Only the connections belonging to one out of three sensor coils are shown. See text for further details. The resistors in the connector box form the impedance correction circuit (see below).
sensor coil. The correction circuit is adjusted such that the measured signal is independent of the position of the cable.

**Lock-in amplifiers**

The lock-in amplifiers (LIA-F-140 and LIA-BF-140 for the first and second set of 9 lock-in amplifiers, respectively, both with a customized range of time-constants, Femto Messtechnik, Berlin, Germany) provide the sine inputs for the coil drivers (see above). The frequencies of the sines are stable within 2 Hz, the amplitudes within 2‰. Phases of the lock-in amplifiers are adjusted such that the outputs of the lock-in amplifiers are maximal. All gains of the lock-in amplifiers are set such that full scale is 10 mV. Low-pass filters are set to –12 dB/oct with a $T_c$ of 1 ms. The output lies within the range of –5 to +5 V. The noise in the output consists partly of noise produced by the lock-in amplifiers themselves (4-7 mV rms), and partly of noise which is interference from the other magnetic fields (maximally 7 mV rms, dependent on the orientation of the sensor coils). Each lock-in amplifier output has an offset (up to 0.3 V), which is caused by small voltages induced in the shielding of the cables connected to the inputs of the lock-in amplifiers. Before and after every experiment the offsets are measured by short-circuiting the inputs in the double shielded connector box (see above).

**Magnetic field calibration**

The three coils used for the calibration of the magnetic fields each consist of four windings of copper wire of 50 µm diameter, wound around a cube. This cube is positioned at a series of heights by mounting it on stands with different lengths. Since the three calibration coils are wound around the same cube, they do not have exactly the same effective area. The relative sensitivities were determined by separately measuring the output of each calibration coil when oriented in the direction of field 1 and connected to the same lock-in amplifier.

**Sensor coil calibration**

A template with orthogonal grooves is used for holding the sensor coil system during the sensor coil calibration. The template is placed into a small perspex holder positioned such that the sensor coil system is in the center of field 1. Calibration of the sensor coil system is performed by subsequently placing the template in three orthogonal orientations and measuring the outputs of the lock-in amplifiers. Sensor coil systems are always attached to the fly in such a way that sensor coils $\alpha$, $\beta$ and $\gamma$ are oriented along the long, transverse, and vertical body axis, respectively.
Measurement of orientation and position