A woodpecker hammer

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Abstract: Woodpecker can be modelled as a low-inertia hammer. It uses the angular momentum of its body, generated by contraction of its leg muscles, to accelerate its head towards the tree, which it is pecking. It appears to peck at a resonant frequency.

Keywords: woodpecker, low-inertia hammer, Lagrangian dynamics, contact dynamics, simulation

1 INTRODUCTION

When a woodpecker chisels wood from a tree, the usual question asked is 'How does the bird avoid brain damage from the sudden deceleration (as high as 1200 g on each impact) when its beak hits the tree?' But a more interesting question is 'How can the bird produce such a high velocity (its beak strikes the tree at over 3.6 m/s) over such a short distance (about 70 mm)?' Another question is 'Why does the woodpecker not fall off the tree with such high decelerations?' [**1**].

Many features of the woodpecker's anatomy are associated with its ability to make holes in wood, which it does in order to uncover insects and grubs for food. The beak is chisel-shaped formed from strong bone overlaid with a covering of horny keratin. Its breadth at the nostrils spreads the force generated during pecking. The beak is attached to the skull by powerful muscles that contract a millisecond before strike, creating a tight, but cushioned structure at the moment of impact and distributing the force of the impact to the base and back of the skull, thus bypassing the brain [**2**]. The nostrils are covered with feathers that keep out pieces of wood and wood powder. The skull is thick with spongy bone and cartilage at the base of the beak that cushions the forces. The brain is comparatively small, resulting in a high relative surface area, which reduces impact stress. The impact of drumming is also cushioned by struts of spongy bone. In the eyes, the vascular layer behind the retina (the choroid) has its own unusual cushioning protecting from internal eye damage. Immediately preceding and during impact, the woodpecker closes both eyes so that the lids restrain them and stop them from popping out of the skull. Even during lightly delivered blows, the eyelids are partly drawn over the corneas. This also protects the eyes from wood dust and debris [**3**]. The pelvic bones are wide, allowing for attachment of strong muscles to the legs and tail. The tail feathers are stiff providing an additional point of contact with the tree. They bend when the woodpecker braces itself to peck, and so may store some elastic strain energy during the pecking cycle. The feet have two toes pointing forward and two pointing backwards which have long and strong nails, so that the bird can hold onto the bark of the tree. The neck is relatively long and thin.

2 MATERIALS AND METHODS

A Road-kill Green woodpecker (*Picus viridis*) provided some measurements (Table 1) and X-ray data (Fig. 1). A short video clip of a Red-headed woodpecker *(Melanerpes erythrocephalus*) of about the same size was obtained from http://www.wrightwood.com/birds.htm

Though the equation of the motion of the woodpecker was non-linear, detailed analytical analysis was not possible, so it was judged that the most

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Table 1 Parameter values used in the analysis

Parameter	Parameter symbol	Value	Unit	Source of data
Head mass	M_H	0.009	kg	Road-kill specimen
Body mass	M_B	0.06	kg	Road-kill specimen
Head inertia	I_H	0.000 125	kgm^2	Road-kill specimen
Body inertia	I_B	0.000 225	kgm^2	Road-kill specimen
Neck stiffness	K_N	7	N/m	Estimated
Neck damping	C_N	0.01	Ns/m	Estimated
Body damping	C_B	1	Ns/m	Estimated
Body spring stiffness	K_B	1000	N/m	Estimated
Gravity	g	9.81	m/s^2	Constant
Dimensions	a	0.047	m	Road-kill specimen
	b	0.098	m	Road-kill specimen
	c	0.117	m	Road-kill specimen
	d	0.03	m	Road-kill specimen

Fig. 1 X-ray

effective verification that could be done was to linearize the system and find the resonant frequency. If the model was found to resonate at the predicted resonant frequency then, bar the linearization, the model could be assumed correct. The non-linear aspects of the system could then be reinserted with a high degree of certainty of the validity of the model.

By performing the following steps the core of the SIMULINK model was tested and assumed, with a high degree of confidence, to be correct.

1. Starting with an unverified non-linear SIMULINK model, the non-linear aspects of the model were removed. In particular, small angle assumptions were added where appropriate.
2. The equations of motion were linearized and the natural frequencies of the linearized system calculated.
3. The calculated natural frequencies were entered into the SIMULINK model, and the model run with no damping and uninterrupted (i.e. with no tree). Provided if the model resonated it was judged that it verified the linear model, as a correct SIMULINK model should resonate at the frequency entered.
4. The non-linear aspects of the system were then reinserted into the SIMULINK model including the impact with tree with a high degree of certainty of success.

Any additional changes to the model were independently tested to ensure that the changes gave the expected results. With a verified SIMULINK model, alterations to individual parameters could be made and their effect on the system investigated. To enhance the speed and rigour of the testing, a program was written in MATLAB that allowed the SIMULINK model to execute repeated runs, with one or two of the parameters altered by a small increment each time.

Once the kinematics of the woodpecker had been investigated, the main engineering principles that enabled it to drum so effectively were catalogued together with a list of the woodpecker's main abilities. Some of the latter were not directly a result of the woodpecker's kinematics, but there seemed to be no reason to constrain the intended creative approach.

3 RESULTS

3.1 The drumming cycle

3.1.1 Beginning

The woodpecker's beak is still in contact with the tree following the previous impact. The woodpecker is stationary and maintains its vertical position by gripping onto the tree with its claws. The fibula and tibiotarsus bones of the leg are almost vertical, with the knee joint nearly touching the tree. The tail feathers, acting as a third point of contact are thrust towards the tree, keep the lower part of the body supported away from it. The body is nearly vertical with the head slightly forward of the centre of the shoulder.

3.1.2 Early swing-back

The woodpecker has started to accelerate backwards, away from the tree. It achieves this by contracting the thigh muscles and extending its legs, exerting a force on the tree. The head is tilted slightly forward suggesting a slight lag behind the body. The body has rotated slightly with the knee moving away from the tree. There is little change in body shape but a slight narrowing of the angle between body and tail feathers.

3.1.3 Mid-swing

The woodpecker has continued to accelerate away from the tree, with the legs providing outwards force. Indication of the leg force direction was made by examining the position of the bone above the claws – tarsometatarsus (which equates to those of the human upper foot), which in this case is still being pressed against the tree with the 'heel or ankle' joint between the tibiotarsus (shin) and the fused bones of the tarsometatarsus, indicating outwards force. The tail feathers have straightened and relaxed so that the lower part of the body can move closer to the tree and the body can rotate more. The head is moving faster than the woodpecker's body, partly due to its distance from the centre of rotation, but also suggesting relative movement between head and body.

3.1.4 Acceleration of the body

It is possible to see daylight close to the woodpecker's claws suggesting that the foot bones are forced outwards as the woodpecker pulls hard back into the tree. The force provided by the legs has started to accelerate the body towards the tree. The lower section of the body also appears to have moved slightly closer to the tree, with a misalignment of the tail feathers suggesting that a force is being applied between the body and the tree. The reaction of the tail feathers gives additional rotational force to the body. The head has moved much further back in relation to the body and is significantly lagged. The woodpecker's chest is thrust forwards suggesting stretching of the body tissues over the upper thoracic cavity, which are primed for contraction.

3.1.5 Impact with the tree

The woodpecker is stationary. The legs and claws have relaxed and are not applying a significant force. The body is very close to the tree with the abdomen almost touching the bark. The tail feathers support the lower body away from the tree so that the woodpecker is almost vertical at the point of contact. The beak is touching the wood and the head is positioned centrally in relation to the body suggesting no phase lag.

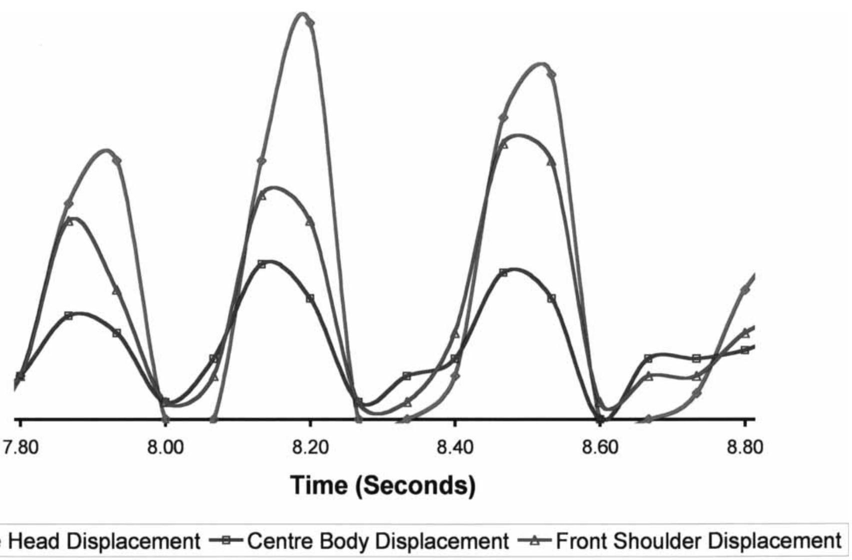

Fig. 2 Simple kinematic analysis from video clip. Displacements (vertical axis) are horizontal

Analysis of film of a Red-headed woodpecker (*M. erythrocephalus*) showed that the body rotates for about 20 ms before the head moves (Fig. 2) suggesting momentum transfer along the neck. Thus although the body moves in an approximately sinusoidal motion, the head moves with more of a saw-tooth profile, reaching a higher velocity in strike. Modelling the woodpecker as a whip system failed to generate the saw-tooth profile describing the head displacement. So the neck is not acting as a simple whiplash. The authors decided to establish equations of motion and produce a dynamic model using SIMULINK. This then allowed them to investigate the important parameters using MATLAB and bring them closer to the final aim – designing a dynamic hammer with low net inertia. The predominant movement of the body is rotational, so the position of the centre of rotation in each frame was decided by taking pairs of adjacent frames of the film and assessing where the point was in the woodpecker's body that moved the least. A judgement had to be made where there was overall translational motion during the drumming cycle.

4 MODELLING THE WOODPECKER

Schematic model of the woodpecker was predominantly based on the kinematics observed in the woodpecker video footage. The model of the woodpecker is shown in Fig. 3 and the dimensional parameters are shown in Table 1.

The following assumptions were made in producing the model:

(a) the tree was modelled as a stiff spring and damper;
(b) the head and body both rotate about the centre of rotation;
(c) the woodpecker's vertebrae and neck tendons were modelled as a spring;
(d) the force input from the woodpecker's legs is assumed to be sinusoidal and horizontal;
(e) the centre of rotation is assumed to be fixed at a distance from the tree equal to the distance from the centre of mass of the head to the tip of the beak.

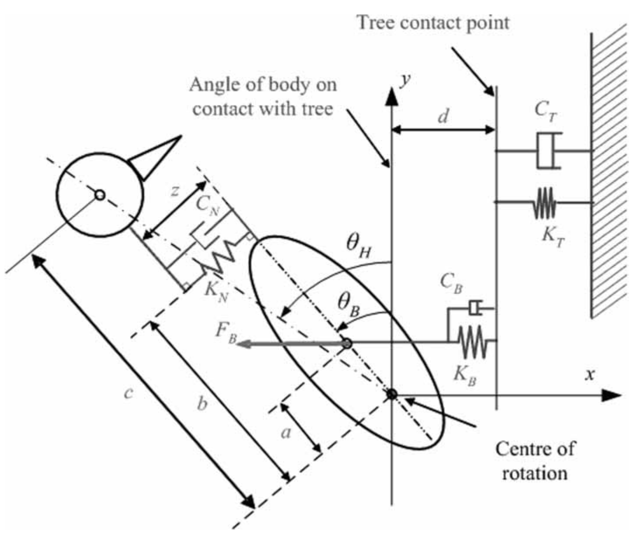

Fig. 3 Schematic model of the woodpecker

The equation of motion for this two-degree-of-freedom system can be obtained by using the Lagrange equation of motion in the following general form

$$Q_i = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i}, \quad i = 1, 2 \tag{1}$$

The body and head angles, θ_B and θ_H, respectively, are selected as generalized coordinates, i.e. $q_1 = \theta_B$, $q_2 = \theta_H$. The generelized external inputs are denoted by Q_i. The functions T, U, and D denote the kinetic, potential, and dissipated energy functions of the system, and are defined as follows

$$\begin{aligned} T &= \frac{1}{2} I_B \dot{\theta}_B^2 + \frac{1}{2} I_H \dot{\theta}_H^2 \\ U &= \frac{1}{2} K_B a^2 \sin^2 \theta_B + \frac{1}{2} K_N c^2 \tan^2(\theta_H - \theta_B) \\ &\quad + M_B a g \sin\theta_B + M_H c g \sin\theta_H \\ D &= \frac{1}{2} C_B a^2 \cos^2 \theta_B \dot{\theta}_B^2 \\ &\quad + \frac{1}{2} C_N c^2 [1 + \tan^2(\theta_H - \theta_B)]^2 (\dot{\theta}_H - \dot{\theta}_B)^2 \end{aligned} \tag{2}$$

where I_B and I_H are the effective moment of inertias around the fixed point O, and can be written as

$$I_B = I'_B + m_B a^2 \quad \text{and} \quad I_H = I'_H + m_H c^2 \tag{3}$$

where I'_B and I'_H are the moment of inertias with respect to centre of gravity of the body and head, respectively.

Note that the stretched length of the neck spring, z, is

$$z = c \tan(\theta_H - \theta_B) \tag{4}$$

Inserting equation (2) into (1) gives the following two equations of motion in terms of the head and body angular positions, θ_H and θ_B, respectively

$$\begin{aligned} I_B \ddot{\theta}_B &= F_B a \cos\theta_B + M_B g a \sin\theta_B - K_B a^2 \sin\theta_B \cos\theta_B \\ &\quad - C_B a^2 \cos^2 \theta_B \dot{\theta}_B + K_N c^2 \tan(\theta_H - \theta_B) \\ &\quad \times [1 + \tan^2(\theta_H - \theta_B)] \\ &\quad + C_N c^2 [1 + \tan^2(\theta_H - \theta_B)]^2 (\dot{\theta}_H - \dot{\theta}_B) \end{aligned} \tag{5a}$$

$$\begin{aligned} I_H \ddot{\theta}_H &= M_H g c \sin\theta_H - K_N c^2 \tan(\theta_H - \theta_B) \\ &\quad \times [1 + \tan^2(\theta_H - \theta_B)] \\ &\quad - C_N c^2 [1 + \tan^2(\theta_H - \theta_B)]^2 (\dot{\theta}_H - \dot{\theta}_B) \end{aligned} \tag{5b}$$

In order to predict the natural frequency of the simulated system, and explore its dynamic properties, the equations were linearized assuming small angles. Inserting $\sin\theta = \tan\theta = \theta$ and $\cos\theta = 1$ gives the following linear model

$$\begin{bmatrix} I_B & 0 \\ 0 & I_H \end{bmatrix}\begin{bmatrix} \ddot{\theta}_B \\ \ddot{\theta}_H \end{bmatrix} + \begin{bmatrix} a^2C_B + c^2C_N & -c^2C_N \\ -c^2C_N & c^2C_N \end{bmatrix}\begin{bmatrix} \dot{\theta}_B \\ \dot{\theta}_H \end{bmatrix} + \begin{bmatrix} a^2K_B + c^2K_N - M_Bga & -c^2K_N \\ -c^2K_N & c^2K_N - M_Hgc \end{bmatrix}\begin{bmatrix} \theta_B \\ \theta_H \end{bmatrix} = \begin{bmatrix} a \\ 0 \end{bmatrix} F_B \quad (6)$$

or in general matrix form as

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{B}F_B \quad (7)$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the mass, damping and stiffness matrices, and $\mathbf{B}$ is the force coefficient matrix. Writing the equations in state-space form gives

$$\frac{d}{dt}\begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}\begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{B} \end{bmatrix} F_B \quad (8)$$

Inserting the parameter values Table 1 into equation (6) and calculating the eigenvalues of the state-space equation (8) gives the system natural frequencies of 25.77 rad/s (4.1 Hz) and 100.65 rad/s (16 Hz). A small neck damping coefficient, $C_N = 0.01$ Ns/m, is introduced to make the model more realistic.

The frequency response of the head and body angles in response to force F_B (represents the forces applied by leg muscles) is shown in Fig. 4. This shows that at the first natural frequency, the motion of the head (and hence its speed) is maximized. The relative phase of the head with reference to the body is about $-90°$ at this frequency. The relative phase is zero at low frequency excitations, i.e. head and body move in phase. Then there is a rapid change of phase from 0 to 180° around the first natural frequency. Thereafter, body and head move in opposite directions (anti-phase) with larger body movements. The width of the region where the phase change takes place depends on the damping in the system, and will increase with increasing damping.

The above analysis does not include the tree. The impact forces, f_T, can be modelled as a function of the penetration δ into the tree as follows

$$f_T = -(K_T\delta + C_T\dot{\delta}) \text{ for } \delta > 0, \text{otherwise } f_T = 0 \quad (9)$$

where the penetration $\delta = -c\sin\theta_B - d$.

Because of the damping term in the tree impact force expression (9), f_T may take a positive value during contact, which is physically meaningless. Therefore, this force is limited to negative values in the simulation. This tree impact force acts on the head along the x-direction. Therefore, it can be introduced to the system equations by adding the term $cF_T\cos\theta_H$ on the right-hand side of equation (5a).

Figure 5(a) shows the head and body motion when the simulation is run by using the non-linear model given by equation (5) and the tree impact force in equation (9), with an excitation force of $F_B = 18\sin(25.5\,t)$. The tree contact parameters are selected as K_T =1000 N/m and $C_T = 10$ Ns/m. The head motion has a discontinuity after the impact for about 0.09 s before moving backwards for the subsequent cycle (Fig. 5(b)), which indicates penetration of the tree. Non-zero penetration corresponds with the contact period. The above tree contact parameters produce a penetration of 2.43 mm. The linear velocity of the head is 2.9 m/s just before contact (Fig. 5(c)) and the beak

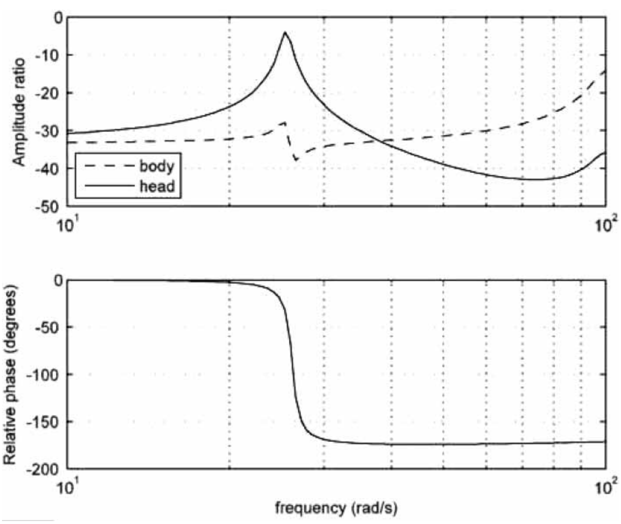

Fig. 4 Frequency response of the woodpecker linearized model

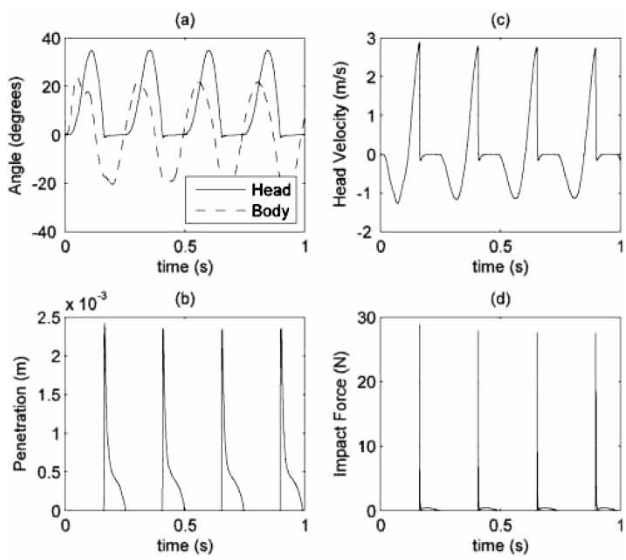

Fig. 5 Woodpecker model response to sinusoidal forcing at the natural frequency, including impact with a tree

hits the tree with an impact force of 29 N. Changing the tree contact parameters K_T and C_T does not affect the impact velocity, but significantly changes the impact force and the penetration. Much higher forces (but less penetration) can be obtained for harder trees with the same impact velocity.

5 DISCUSSION

The power required to accelerate the head of the Green woodpecker, which was dissected is about 8.7 W. The neck muscles weighed 3.3 g, so their specific power output would have to be approximately 2.6 W/g, which is about three times greater than the most active muscles known – the flight muscles of insects. Therefore, the power must be coming from the muscles in the body. By varying the phase relationship of the movement of the head with that of the body, the bird is able to transform the more-or-less sinusoidal movement of the body into a more saw-tooth movement, indicating higher speed impact than would be possible with a more obvious oscillating system. By working at a resonant frequency the bird can use its muscles still more efficiently.

Unfortunately a number of parameters had to be estimated, since the natural system is far more complex and variable than a simple mechanical model. However, it is considered that there was enough hard data and observations for the results and conclusions reported here. With rather more information it would be possible to predict the mechanical behaviour of the animal under a variety of conditions and to see how much of its behaviour is dictated by mechanics.

One of the reasons for studying the woodpecker was to derive a design for a lightweight hammer. It was reasoned that the woodpecker is a bird, therefore has to fly and therefore is constructed as light as possible. The mechanism, which has emerged as a result of the model reported here – momentum transfer from body to head of the woodpecker – has been used in the design of a novel hammer (Fig. 6 – designed by Dr G. Whiteley). A rotating crank is connected by means of a rod to the casing, so that the motor plus its mounting oscillates about a central pin. The motion is transferred to the hammerhead by a parallel springs. The constants can be calculated from the woodpecker data. This hammer has a number of advantages over conventional design. It was originally conceived for use in space exploration, where it has no net inertia

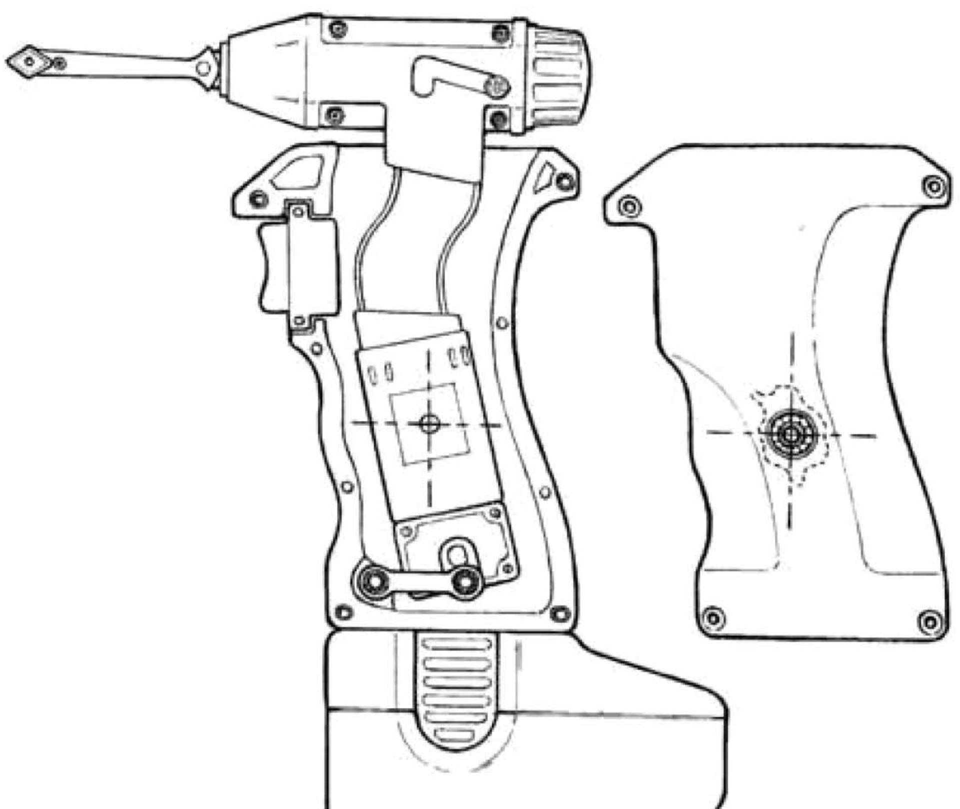

Fig. 6 General arrangement (GA) of a woodpecker hammer

until it comes into contact with an object, and even then the force delivered can be tuned. It could also be used where working space is at a premium, such as dentistry or surgery, or to remove flash from castings, and there will be many other uses, which will be realized only when a prototype has been made and its performance assessed. This part of the process is on hand.

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