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Development of a Wing-Flapping Flying Replica of the Largest Pterosaur

A.N. Brooks, P.B. MacCready, P.B.S. Lissaman, and
W.R. Morgan, AeroVironment Inc., Monrovia, CA

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DEVELOPMENT OF A WING-FLAPPING FLYING REPLICA OF THE LARGEST PTEROSAUR

Alec N. Brooks *
Paul B. MacCready **
Peter B.S. Lissaman ***
Walter R. Morgan ****

AeroVironment Inc.
Monrovia, California

Abstract

Fossil evidence exists for a gigantic pterosaur, Quetzalcoatlus northropi. This flying reptile, with a wingspan estimated at 11 m, represents the largest flying animal known. A project is underway to create a full-sized flying replica, designated the QN^{tm}* replica, to be propelled by wing flapping and controlled by radio. The need for the reconstruction to fly in a manner analogous to the original creature is requiring engineers and paleontologists to combine forces to bridge gaps in knowledge about natural flight.

The replica will use electric servo-motors to flap, sweep, and twist its wings. The head and fingers (located about halfway out on the wing leading edge) will also be servo driven, for use as lateral control devices. An autopilot will maintain angle-of-attack, bank angle, and sideslip angle. Pitch control will be effected using variable wing sweep, with the wings pivoting about a pair of approximately vertical axes located in the body.

Introduction

Pterosaurs were a class of flying animals distinguished by their reptilian features and slender membranous wings, and lived during the Mesozoic era, between about 200 million and 64 million years ago. The wings of pterosaurs are formed by the greatly elongated fourth finger of the hand. The larger pterosaurs had no tails, and were thus 'flying wings'. All pterosaurs were very lightweight, and had very thin-walled hollow bones. An excellent introduction to pterosaurs is given by Langston in a Scientific American article[1]. The name 'pterosaur' derives from the Greek words pteron and sauros, literally 'winged lizard'.

In 1975, fossil remains of a giant pterosaur were found in West Texas by Lawson[2], working with Langston. The new species was named Quetzalcoatlus northropi, after the Aztec feathered serpent god, Quetzalcoatl, and the Northrop Aircraft Company, which built several giant flying wings in the 1940's. Except for one vertibra, only some of the wing bones were found, and many of them were crushed and distorted. As a result, a detailed reconstruction has not been possible. The existing wing bones suggest a wingspan of about 11 m. The mass is much more difficult to determine. Based on considerations of power required to fly, the mass must have been 100 kg or less.

Another group of fossils was found at the same time for a smaller, but similar creature. This group contained nearly complete skeletal remains of several specimens. Due to the similarity with the larger fossils, this group was given the name Quetzalcoatlus sp. (sp. is an abbreviation for 'species'; when more is known about these fossils, a genus name may be assigned). Langston is currently reconstructing a complete skeleton of Quetzalcoatlus sp. to provide insight into what the larger creature might have been like.

The QN^{tm} Replica project

In April 1984, a National Air and Space Museum (NASM) project was initiated to investigate the feasibility of constructing a flying replica of Quetzalcoatlus northropi (figure 1). At the beginning of the project, AeroVironment convened a QN^{tm} Replica Workshop at the California Institute of Technology to help assess the overall feasibility of building and flying the replica, to make plans for later phases of the program, and to arrive at a consensus about the size, shape, and operating features of the creature. The workshop brought together experts in paleontology/paleobiology, ornithology, aerodynamics, stability and control, robotics, and also representatives of the NASM.

The workshop concluded that construction of the replica was certainly possible, with the two main problems being stability and control, and

* Manager, Fluid Dynamics Projects, Member AIAA
** President, Fellow AIAA
*** Vice-President, Aerosciences Division, Associate Fellow AIAA
**** Manager, Design and Development Center, Member AIAA

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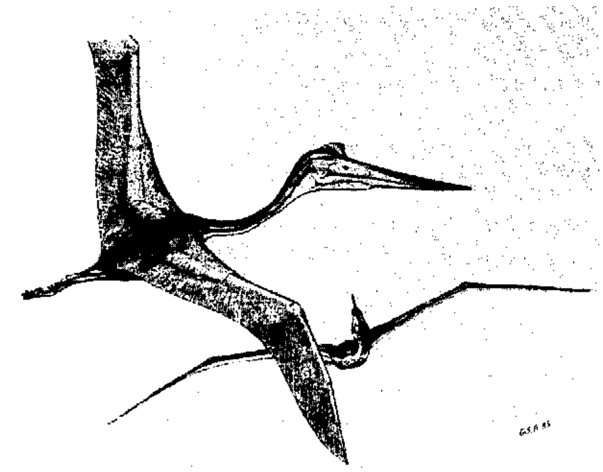

Figure 1. Artist's rendering of Quetzalcoatlus northropi (Gregory Paul, Artist).

wing-flapping propulsion. In December, 1984, a press conference was called at the NASM to announce the positive results of the initial feasibility study. With AeroVironment as prime contractor, the project then continued into the development stage with major funding from Johnson Wax supplementing the NASM support.

Overall approach to QN^{tm} Replica Development

The plan for creating the final replica was to solve the major technical problems one at a time, using a series of increasingly complex flight models. Stability and control were perceived to be the really difficult problems, and so were addressed first.

The stability/control challenge arises for several reasons. First, Quetzalcoatlus northropi had no horizontal tail to deal with with stability and control in pitch. Also, its wing may have been unstable in pitch, due to its undercamber and lack of sweep. Second, there is no vertical fin or rudder to provide lateral control, and there is a long neck and large head, which produce destabilizing directional derivatives.

To fly stably, the creature must have made use of active control. For example, variable wing sweep was probably used to continually adjust the fore/aft position of the center of lift relative to the center of gravity. Humans utilize active control in many situations, such as riding a bicycle or standing on one foot, without being aware of it — it is simply instinctive. For the replica, this control involves motions which might seem natural: wing tips forward produce a pitch-up while if the head turns to look to the right, a right turn is initiated.

The flight models being tested prior to building the final 11-m replica include a pitch control development model with a standard aircraft configuration, a half-scale lateral control development model with pterosaur configuration, and a half-scale, realistic flapping model.

All stability and control analyses and autopilot control loop design for the QN^{tm} replica project are being performed by Henry R. Jex, of Systems Technology, Inc.

Pitch Control Development Model

Pitch stability and control on the replica will be effected using variable wing sweep, actively commanded by an autopilot. A 2.5-m span radio-controlled glider was built to develop this capability. It had a standard configuration but incorporated servo-driven variable-sweep wings, pivoting about a vertical axes in the body. During initial flights, variable wing sweep provided the sole pitch control, with a fixed horizontal stabilizer on the tail to provide stability. An autopilot was then added which commanded the wing sweep angle, using sensed angle-of-attack and pitch rate. Test flights continued using smaller and smaller horizontal tails, as the autopilot feedback gains were optimized. The final flights of this model were made with a very small horizontal tail, barely extending past the tail boom to which it was mounted.

The servo used to drive the wing sweep was a large, commercially available model airplane unit, which was barely adequate for the job. Its response bandwidth was marginal for the task of maintaining pitch stability, resulting in considerable 'hunting' of the wing sweep position in flight. The final replica will use a custom made servo with faster response.

Lateral Control Development Model

A half-scale (5.5 m span) gliding model is being used to develop the lateral control functions. This model, shown in figure 2 along with many members of the development team, has the general configuration of the final replica, but for simplicity does not incorporate variable wing sweep. For this vehicle pitch control is achieved using trailing edge elevators on the inboard section of the wing. The wing structure is rigid, made of expanded polystyrene foam with a carbon and balsa spar, and uses a reflexed Liebeck airfoil.

Lateral control surfaces include the head, which pivots about the neck to 'look' from side to side and generate yawing moments, spoilers about halfway out on the wing which can create drag and reduce lift, and ailerons on the trailing edge of the wing. On the next model, the spoilers will be replaced by more realistic moveable fingers, and the ailerons by variable wing twist. An autopilot controls these surfaces using signals from a sideslip vane and a yaw rate gyro, as well as commands from the ground.

With a weight of more than 11 kg, this model is too large to be hand-launched from a hill, so a winch tow is used. To enhance stability while on tow, an auxiliary set of tail surfaces is fitted, which is dropped off after completion of the tow. The auxiliary tail also has wheels for takeoff and a parachute for recovery after it is dropped. The model is fitted with an emergency parachute which can be deployed in the event of loss of control.

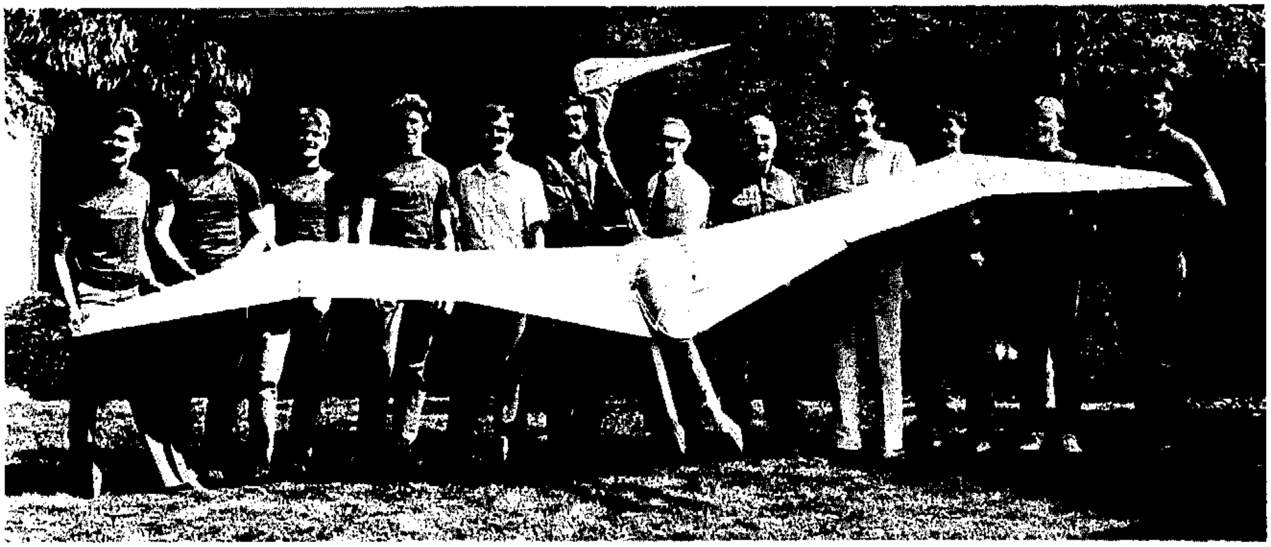

Figure 2. The lateral control development model and the project team.

Figure 3 shows the model in flight shortly after release of the tail.

The head is commanded to provide a stabilizing and correcting yaw moment by turning toward the relative wind at an angle greater than the sideslip angle. Yaw damping is added to the head command using the sensed yaw rate. The spoilers are principally used as yaw dampers. The ailerons have been initially directly commanded by the pilot, but later will be controlled by a wing-leveling autopilot.

Flights with this model have shown stabilization in yaw to be a very difficult problem, analogous to trying to fly a normal airplane with the vertical tail moved from behind to in front of the wing (i.e. with negative directional stability). Successful flights have been made under nominal flight conditions, but the system is not yet 'robust' in that under some other conditions apparently related to large excursions from equilibrium, such as excessive airspeed or momentary radio 'glitches', complete loss of control is possible. This occurs when the sideslip angle increases to an angle at which the head and hands can no longer provide adequate restoring forces. In this instance the head acts as a 'weathervane' and the model quickly turns sideways and falls uncontrollably, necessitating a parachute recovery. Further development of the system will reduce the probability of loss of control.

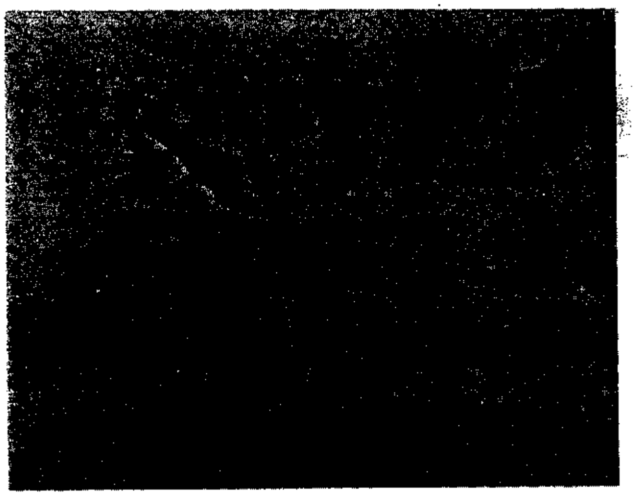

Figure 3. The lateral control development model in flight just after release of the auxiliary tail boom.

Half-Scale Flapping Model

After development of the lateral autopilot system is complete, a realistic flapping-wing half-scale model (5.5 m wingspan) of Quetzalcoatlus northropi will be built and flown. This model will be the prototype for the final full-scale replica, incorporating all of the final control functions. It will be the same weight and size as the lateral control development model, and will also be winch-launched with an auxiliary tail boom. Before flight testing with flapping, it will first be flown as a glider until all stability and control problems are resolved. Flapping tests will proceed gradually, starting with captive tests with the vehicle mounted on top of a moving van, then proceeding to flight tests with small flapping amplitudes with the auxiliary tail still attached.

Details of the flapping aerodynamics and the flapping mechanism design are given below.

Ornithopters

Although birds make flapping flight look easy, it has proven to be a challenge for man to mechanically reproduce. Man-made flapping-wing flying machines are known as ornithopters. Attempts to build ornithopters can be split into two categories: man carrying, and hobbyist/toy. Only the hobbyist/toy ornithopters have shown any successes at all.

There are many good small rubber-band powered ornithopters, with wingspans of 0.5 m or less. Rubber bands are a good power source because they can deliver the necessary torque directly, without resorting to a gearing system. However, rubber bands do not have high energy storage density, so flight duration is quite limited.

Larger ornithopters have been built using compressed gas or model airplane engines for propulsion. At the QN^{tm} Replica Workshop, two of the participants presented results of experiments with large 3-m span radio-controlled ornithopters.

Bennett conducted his doctoral research on ornithopter aerodynamics[3] and later tested a large ornithoper mounted on a moving test rig that was instrumented to measure lift and thrust. The wings were initially built to allow twisting as well as flapping, but proved to be too flexible in torsion. A torsionally stiff set of wings that eliminated twist were used for the tests. This wing was stalled during much of the flapping cycle, and it was found that net thrust and lift could not be generated simultaneously.

Flight test films of a large twin-engine radio-controlled ornithoper were shown by Adkins[4]. One engine drove a variable amplitude flapping mechanism, and the other was mounted in the nose driving a normal model airplane propeller. Both engines would be started on the ground, with the flapping amplitude controller set to zero. The model could then take-off as a normal airplane and climb to a safe altitude. The front engine was then throttled back, and the flapping amplitude was slowly increased. In the event of incipient instabilities, the flapping could be immediately shut down, and a normal landing could be made. While flapping, this model was capable of climbing at very steep angles.

Aerodynamics of Flapping Flight

Flapping-wing propulsion is relatively simple in concept, but accurate calculations are difficult due to the complexities of the intrinsically unsteady flowfields involving both viscous and potential unsteady effects. In simplest terms, if a wing in a uniform flowfield is oscillated in heave only (no pitch change), then a net thrust can be developed. The basic case is that of a wing initially at zero angle of attack. When this wing undergoes heave motions, the local velocity vector is inclined, causing the lift vector (approximately perpendicular to the local velocity) to be inclined forward, resulting in a thrust component. This thrust is developed on both up and downstrokes, while over a complete cycle the lift component cancels out. If the wing also undergoes pitch angle oscillations properly phased with the heave oscillations, the thrust generation can be more efficient, with smaller variation of the lift coefficient during the flapping cycle. By biasing the pitch angle of the airfoil, a net average non-zero lift can be created along with thrust. This is the basis of flapping flight. Based on the foregoing, it can be seen that a condition for net thrust as well as net lift is that the lift on the downstroke is greater than the lift on the upstroke. It is noted that this condition provides the mechanism for work to be done by the flapping drive mechanism which is then transformed, with an inevitable efficiency loss, into propulsive power.

The fluid mechanics of flapping flight involves intrinsic unsteady effects. To establish a basis for the discussion following we will list them here. The analysis of unsteady potential flow is very well understood. The principal elements here which are not present in steady flows are the spanwise shed vorticity downstream of the wing and the pressure perturbations on the wing due to the temporal derivatives of the potential (sometimes referred to as apparent mass terms). While the exact equations for the fluid dynamics can be simply formulated, the complexity of the integrals required for solution severely limits any closed form analytical solutions and requires numerical computation for most realistic geometries. The unsteady effects in the viscous (boundary layer or separated flow) regions are still incompletely understood. In addition, the nonlinear effects of large perturbations add further complexity and in general inhibit separation of variables or superposition of various fundamental situations such as the flap-with-no-lift and the lift-with-no-flap cases.

Observations of wing motion in some bird flight modes indicate that the wing-stroke is very complex involving fore and aft as well as up and down wing motion, extreme articulation (changes in wing angle of incidence) and large flapping motions, all with pronounced spanwise variation. However these modes often involve very low speed or highly accelerated flight. For regular cruising flight with steady average forces it is probable that the wing motion is much simpler. This is representative of the mode with which we are concerned.

The wing flapping dynamics will be designed to incorporate essentially a uniform vertical flapping motion pivoting about the root, with articulation achieved by the aero-elastic effects of a spanwise-taylored torsional spar stiffness, assisted by servos which directly twist the wings. Thus, for this project it is desirable to obtain some crude guidelines on appropriate flapping lift distributions and on the consequent propulsive efficiency, and to use these as a starting point, with the prospect of fine-tuning the propulsion dynamics by actual testing. No unsteady viscous analysis has been employed on the basis that these effects occur only near the stall angle of attack. It has been assumed that, provided the steady state stall angle is not exceeded, the unsteady viscous effects will not be significant.

Two potential flow models (Kroo[5] and Bennett[3]) have been used as guidelines for the flapping design. A simplified quasi-steady lifting line model has been given by Kroo[5] which does not include the effects of both spanwise shed vorticity and apparent mass, but does incorporate articulation and a realistic flapping motion. This model gives an optimal flapping lift distribution which corresponds to the steady-state lift distribution which would result in a spanwise downwash varying like $|y|$, where y is the spanwise parameter (y=0 at the root, y=1 at the tip). This is a special case of the general steady wing theory result that, on a wing of spanwise circulation $\Gamma(y)$, the induced drag is minimized, subject to an integral weighting parameter $f(y)$, under the condition that

$$\int_0^1 \Gamma(y)\, f(y)\, dy = P$$

is constant. This is satisfied by selecting $\Gamma(y)$ such that the steady state induced downwash is proportional to the weighting function, $f(y)$.

If $f(y)$ is take as proportional to the vertical motion at the spanwise station y, it will be noted that P represents the input flapping power. Putting $f(y) = 1$, representing heaving motion, recovers the classical elliptical loading as optimal, while the case $f(y) = |y|$ represents the motion of flapping about a horizontal hinge at the wing root. The flapping circulation associated with this downwash is a characterisic saddle-back distribution. The design flapping lift distribution is shown in Figure 4 where it is superimposed on the steady state elliptical mean lift distribution to indicate the maximum and minimum lift during a cycle.

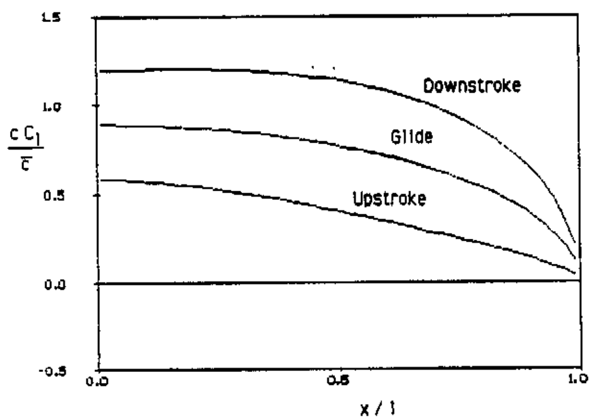

Figure 4. Optimum flapping lift distributions at mid-points of upstroke, downstroke, and glide.

The thrust coefficient, T_c, is nondimensionalized similarly to the lift coefficient, thus it is defined as the thrust divided by the wing area and dynamic pressure due to forward flight speed. Figure 5 shows how the thrust coefficient and the flapping frequency influence the required variation of total lift coefficient. Also shown are the predicted propulsive efficiencies and the design point for the half-scale replica. The prediction of an efficiency in excess of 98 percent is evidently a consequence of the factors ignored in the quasi-steady model. The parameters at the design point are: flapping frequency, 1.2 Hz; average lift coefficient, 0.7; flapping lift coefficient, ±0.32.

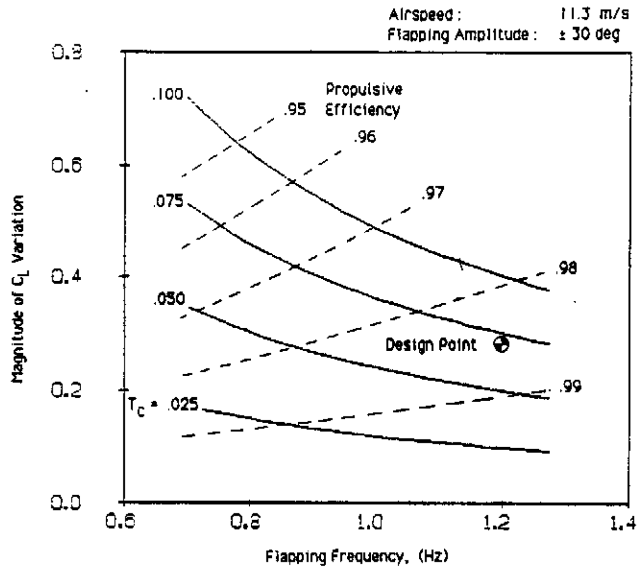

Figure 5. Magnitude of the fluctuating lift required to produce given thrust coefficients as a function of flapping frequency.

The model of Bennett takes into account the spanwise shed vorticity, the apparent mass terms and the lifting surface effects (as opposed to lifting line). However it is for a non-articulated rectangular wing undergoing heaving motions. However, it can be assumed theoretically correct for this simplified geometry. This model gives a limit case for vanishing frequency (the quasi-steady case) and thus provides an estimate of the error involved in the quasi-steady case.

For a reduced frequency (based on semi-chord) of 0.13 and a thrust coefficient of 0.1, Bennett gives the ratio of the actual thrust to the quasi-steady value to be 0.75 for an elliptical planform of aspect ratio 14 and 0.5 for a rectangular planform of the same aspect ratio, while the propulsive efficiency is 0.92 and 0.75 for each planform, respectively.

The difference between the Kroo and Bennett results, although in part due to different parameters, illustrate some of the uncertainties which have made it prudent to make design allowances for a low propulsive efficiency and to be able to modulate the wing articulation.

At present, the design strategy is to use a selected flapping lift distribution and to determine by approximate methods the local induced and flapping-created vertical flows so that the proper twist or articulation of the wing can be achieved. For the replica, this articulation is of the order of 45° at the wing tip, considerably greater than the twist of the order of a few degrees associated with the spanwise variation of the desired flapping loading. It is unlikely that the twist can be either predetermined or controlled to so fine a degree, and as a result the flapping propulsive efficiency will suffer and it will be necessary to increase the power input to achieve the desired performance level.

Mechanism and structure

The predicted efficiency of flapping flight is quite high (at least in excess of 80 percent), and yet man-made ornithopters always seem to be very inefficient. This may be due mainly to the large oscillatory motions required to flap the wings. Fairly large forces are required at the end of each flapping stroke to slow the wing and reverse its direction. This in itself does not require energy because during deceleration the force is in opposition the direction of motion so work is done on the mechanism. If this work is stored, it can be recovered as the wing accelerates in the opposite direction. It is believed that birds use springy tendons to store this energy. Many ornithoper attempts have not adequately addressed this issue, and therefore operate nonconservatively, and thus dissipate part of the kinetic energy of the flapping motion. The QN^{tm} replica will utilize a spring to balance the inertial flapping loads, with the resonant frequency of the system matched to the flapping frequency. In addition, the spring will be pre-loaded to balance the steady state gliding lift loads.

Flapping mechanism design philosophy

The flapping mechanism for the QN^{tm} replica requires three independent motion controls: flapping, sweeping, and twisting. The flapping and sweeping motions operate on both wings symmetrically, while the twisting motion must be capable of operating differentially for roll control.

Several options were considered for the wing-flapping mechanism of the replica. One of the ground rules from the start was that it should be electric powered to keep the noise level low. An electrically-driven hydraulic system has many advantages, but was ruled out due to unacceptably low efficiency.

Another option, similar to systems used in most previous ornithopters, is a geared DC motor which drives a reciprocating mechanism. In this case the motor runs steadily at high speed, but with variable torque throughout the flapping cycle. The phased twisting of the wings would be accomplished with a mechanism. This requires a motor controller that varies the applied voltage to the motor over the flapping cycle in order to maintain constant speed. If remote control of flapping amplitude is desired, the there must be some means of varying the geometry of the drive mechanism. The mechanism of the Adkins ornithopter had these features (but not variable sweep), and was quite complicated.

The mechanism design chosen for the replica uses servo motors to produce all of the wing motions, including flapping. The flapping servos use DC motors, as in the previous option, but instead of using a reciprocating mechanism for motion reversal, the motors in the servo reverse direction. The advantage of this system is that the wing flapping motions are easily modified, since this information is stored in software, rather than hardware.

The mechanism for the half scale replica uses ball-nut drives to convert high-speed rotary motion of the motors into low-speed linear motion. The wing roots are pivoted on a gimballed joint at the 'shoulder', and a stub spar extends inward to nearly the centerline of the body. Links from the flap and sweep ball-nuts attach to the end of the stub spar. The partially completed mechanism of the half-scale replica is shown in figure 6. The flapping motion is driven by two Astro-Flight model 60 Samarium Cobalt DC motors geared 1-1 with the ball screw. These motors are each rated at 900 W peak output power. A single sweep motor, an Astro-Flight 05, directly drives the sweep ball screw.

Spring Balance

The flapping mechanism incorporates a spring which balances inertial and steady state lift loads in the mechanism. The spring rate is chosen such that the natural frequency of oscillation of the mechanism is equal the flapping frequency, and the preload is set to balance the average lift loads. In addition to the wing inertia, the inertia of the motor armatures, gears, and other rotating components must be considered when calculating the appropriate spring constant. The motor inertial loads account for 85 percent of the total. Each motor is required to

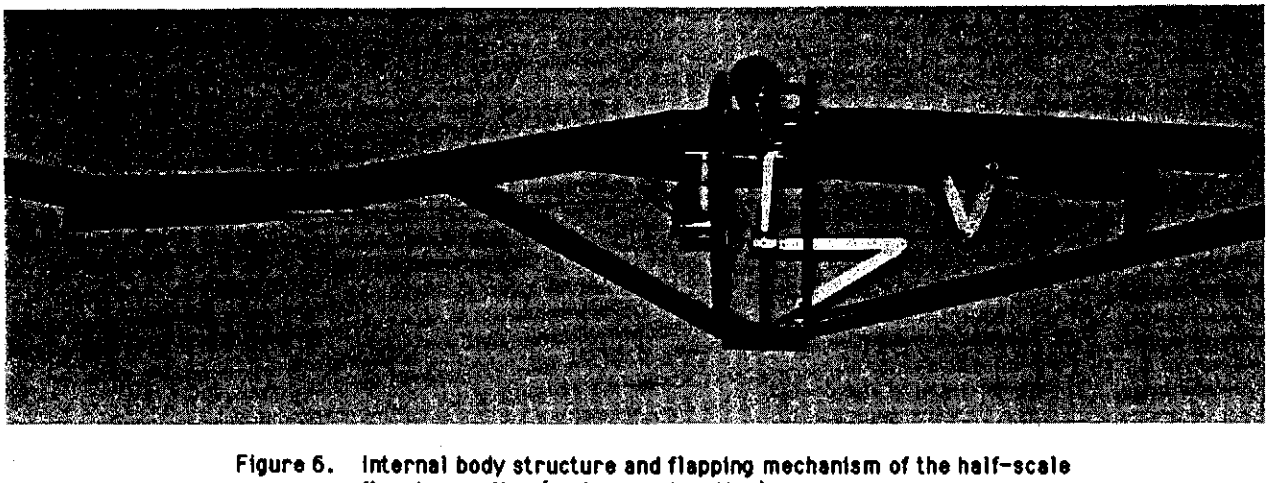

Figure 6. Internal body structure and flapping mechanism of the half-scale flapping replica (under construction).

accelerate from zero to 9000 rpm and back to zero again twice during the 0.83-second flapping cycle.

The spring balance for the replica is made of rubber of the type used on rubber-powered model aircraft. The spring is about 0.15 m long, with multiple strands of rubber. It is fixed at one end to an attachment point on the neck, about halfway between the body and the head. The other end is connected to a length of braided fishing line. This line winds up on a spool attached to the intermediate shaft of the main gearbox. The line is able to wind on either side of the spool, to allow the spring to the spool. In order to balance the steady state lift loads, this point is set to occur at an appropiate anhedral (wing tips below horizontal) position of the wings. The peak compressive loads in the neck due to the spring are about 350 N. Operation of the spring balance is depicted in Figure 7.

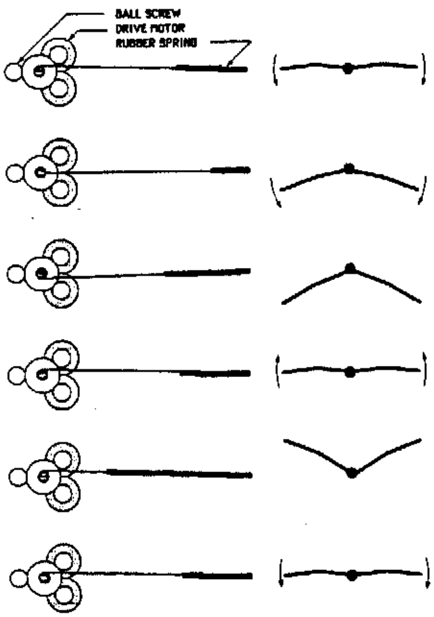

Figure 7. Operation of the spring which balances the inertial loads associated with flapping.

The spring balance relieves the flapping motors of heavy braking and acceleration loads. If the spring balance were not used the motors and servo amplifiers would have to be significantly larger, and energy would be wasted due to the higher currents required. Figure 8 compares the current and voltage requirements for each motor over one flapping cycle with and without spring balancing of the inertial loads.

<u>Wing Twist</u>

The wings must twist through large angles during the flapping cycle to maintain the proper loading. The replica's wings will be made flexible in torsion, allowing most of the required twist to be achieved passively by aeroelastic effects. Small servo motors will be used to fine-tune the elastic

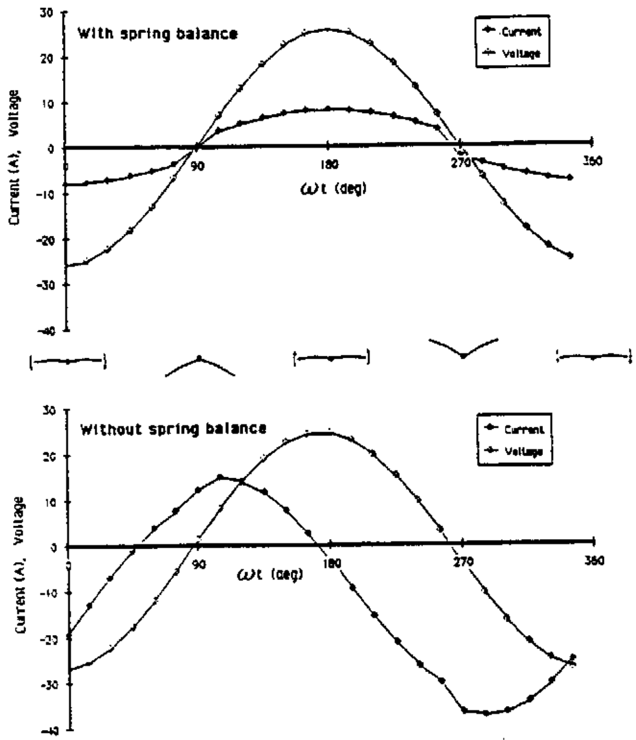

Figure 8. Comparison of current and voltage requirements for each flapping motor with and without the spring-balance.

twist. The spanwise distribution of torsional stiffness of the spar is calculated to give the proper torsional deflection given the variation of lift loads and required twist angle over the flapping cycle. In addition, the wing is built with a calculated 'pre-twist', such that in gliding flight, the wing will be deflected to the proper shape.

The wing twist servos each actuate a torque tube that runs inside of the main spar to the point about halfway out the span where the large fourth finger meets the hand. The twist servos will be commanded to follow a certain twist angle over the flapping cycle. If the passive twist accurately follows the desired twist, then the twist servos follow the motion with virtually no load. Otherwise, the twist servos apply torque to force the wing to the correct twist angle. The servos twist the wings differentially for roll control.

<u>Power System</u>

The electric power system for the replica demands very high power density from the energy source, with reasonable energy density. To meet these criteria, the replica will use high-discharge-rate sintered-annode nickel-cadmium cells. These are commonly used in electric-powered model aircraft, and can produce about 250 W/kg over a discharge of 4-5 minutes. The half-scale replica will carry two strings of 28 "sub-C" size cells, which have a total weight of 3 kg.

Delivery of the power to the various servos will be through commercially available FET-based servo amplifiers. These amplifiers are pulse-width-modulated at 22 kHz, with full four quadrant operation in the voltage/current plane. This allows bi-directional motor drive with dynamic braking.

The radio receiver and autopilot circuits will be powered with a separate 5 V battery pack.

Control and Autopilot System

The control system for the replica will incorporate lateral and pitch autopilot functions. The pilot on the ground will command the angle-of-attack, turn rate, and flapping amplitude. The control system is based on standard model alplane radio control (RC) hardware, customized where required. Standard RC systems command each servo with pulse-width modulated (PWM) signals. The autopilot functions for the replica are accomplished by converting the PWM signals to analog levels, then adding in appropriate amounts of sensed quantities (e.g. yaw and pitch rates, angle of attack, sideslip angle). The resulting signal is then either converted back to a PWM signal for driving standard model servos, or sent directly to the FET servo amplifiers for driving the custom servos.

The wing-flapping servo amplifier must receive a flapping waveform signal. The simplest case is a sine-wave at the flapping frequency with its amplitude set by the pilot's command. The wing twist signal is generated by scaling and phase-shifting the flapping signal. The flapping motion may also require cyclic motion of the wing sweep servo to minimize pitching while flapping. For the greatest flexibility, these signals will be generated by a digital circuit which scans through lookup tables stored in read-only memory.

Conclusions

The task of creating the QN^{tm} replica requires creative application of a diverse range of existing technologies to find engineering solutions to problems that nature solved millions of years ago. As development of the replica has progressed, we have developed a great deal of respect for nature's solutions.

The replica will have only a handful of motion degrees of freedom, controlled by relatively 'dumb' autopilot circuits. The actual creature had a great number of individual muscles, controlled by a brain with relatively immense processing power. In addition to flying, the creature was also cabable of standing, walking, and running for takeoff. The replica will not attempt any of these feats -- Man-made robots have not yet even come close to recreating the versatility and dexterity of the human body.

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