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Experimental Study of Oscillating-Wing Propulsion

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In this experimental study of flapping-wing thrust, a wing of 8 in. span and 2 in. chord was oscillated in a low-speed wind tunnel. The driving apparatus produced nearly sinusoidal heaving with superimposed pitching of variable amplitude and phase angle. The flapping frequency range of 0-8 Hz produced reduced frequencies for which flow separation was unlikely to occur, based on the measured static characteristics of the test airfoil (NACA 0012) over the Reynolds number range of interest (25,000-40,000). The average thrusting effort of the wing was measured and plotted in coefficient form against reduced frequency, with pitching amplitude and phase angle as parameters. Comparisons of the results with theoretical predictions and previous experimental work were made. In general, the results show approximately linear dependence of thrust on reduced frequency and best performance at phase angles of 90-120 deg of pitching lagging heaving. Although thrusting effort was produced for all pitching amplitudes, including zero, the highest readings were obtained for the maximum pitching amplitude of 12.1 deg.

Introduction

THE purpose of this work was to obtain accurate and repeatable measurements of the average thrust produced by a chordwise-rigid oscillating wing and to study the variation of average thrust with various motion parameters. This is motivated by the fact that research in oscillating-wing propulsion has been dominated by theoretical studies, with very few precisely defined experiments. Of these the most notable include the experiments in 1922 by Katzmayr,[1] where he measured the change in net drag of an airfoil harmonically oscillating about a midchord point. Also, Silverstein and Joyner[2] in 1939 conducted a short series of oscillating airfoil tests for the purpose of verifying Garrick's[3] theoretical predictions. The most comprehensive work to date has been the 1968 experiments by Scherer[4] on an oscillating finite wing in a water channel. Average thrust and efficiency were measured for various motion parameters and the results were compared with an analytical model. Instantaneous thrust values were measured in 1974 by Bennett, Obye, and Jeglum[5] on an oscillating airfoil, and Fejtek and Nehera[6] measured instantaneous and average thrusts in 1979 on a root-flapping rigid wing with no pitching. Also in 1979, Archer, Sapuppo, and Betteridge[7] measured the mean propulsive thrust and efficiency of a chordwise-flexible root-flapping wing.

The present experiments are similar to Scherer's in that a rigid, finite-aspect-ratio wing is harmonically oscillated in plunge and pitch motions. Therefore, the difficulties and uncertainties of a "two-dimensional" test are avoided and the kinematics are precisely defined. Also, motion parameters similar to Scherer's were used as experimental variables, although different ranges were covered, including a larger variation in reduced frequency. Note also that these tests were performed in a wind tunnel; hence, Scherer's concerns with the water channel's wall and surface effects were avoided.

Along with the results, this paper gives a detailed description of the test apparatus. In the authors' experience, the development of equipment and techniques for reasonably satisfactory measurement of the tangential forces in small-scale flapping wings is a considerable challenge in itself. The thrusts to be measured are on the order of thousandths of a pound, and the elastically suspended drive has a perverse tendency to mask the desired signals with self-generated resonances. Consequently, appreciable development was required to refine the apparatus which gave the results reported here.

Naturally, the question of comparison with theory arises. The authors are currently developing a theoretical approach tailored to the particular conditions characterizing their experiments. As for comparison with the theoretical work of others, this would involve making changes or invoking assumptions which would not allow straightforward conclusions to be drawn. For example, Garrick's[3] theory is restricted to a two-dimensional airfoil with small-perturbation motions and no viscous effects (other than the Kutta condition), and the finite-wing analysis of Chopra and Kambe[9] is likewise linearized and inviscid. Also, their solutions are not in a closed form and involve considerable numerical integration. Scherer's[4] experiments were similar to the authors' in that he used whole-airfoil oscillation with pitching, but his theoretical treatment of leading-edge suction is at variance with the authors' interpretation, and he also offers no closed-form expressions for net thrust. Archer, Sappupo, and Betteridge[7] are concerned with root-pivoted flapping, which is sufficiently different from the pure plunging case to encourage a fresh start rather than the extensive modifications required for a direct comparison. In short, it was judged desirable to present now the experimental methods and results for the information of other researchers, and to reserve the theoretical development and comparison for a future paper.

Experiments

Description of the Equipment

The wing tested is shown in Fig. 1. It had a rectangular planform of 8 in. span and 2 in. chord, with a chordwise-rigid NACA 0012 airfoil. It was constructed of thin balsa-sheet laminations, with the sheet dimensions predetermined by a scaled-up layout drawing. The airfoil was shaped from this outline, the final sanding being done under magnification. Hence, a profile of reasonable accuracy was obtained for the 2 in. chord. The wing was finished by being covered with thin

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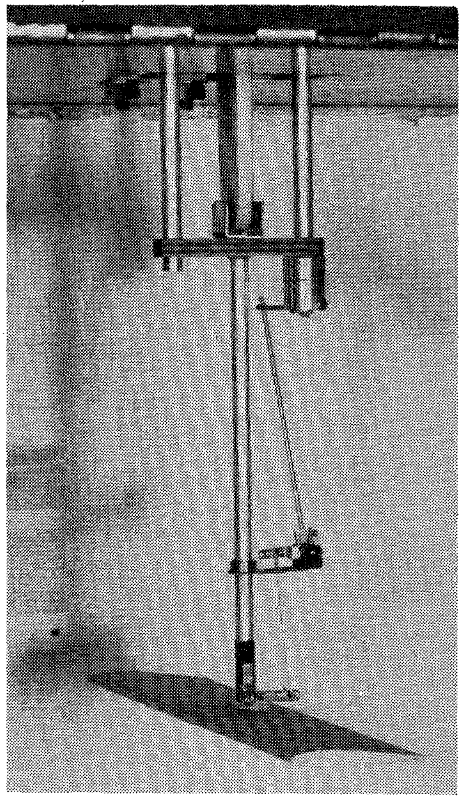

Fig. 1 Wing model in wind-tunnel test section.

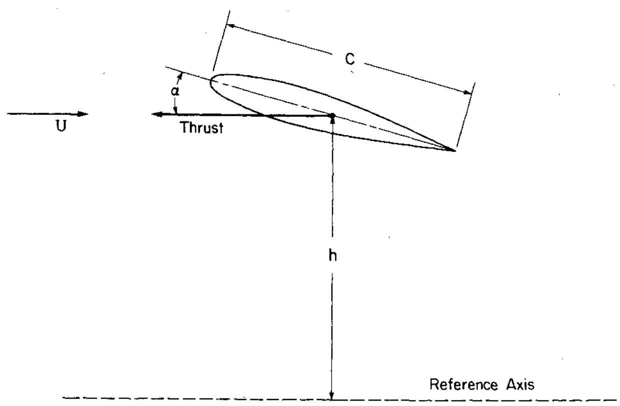

Fig. 2 Schematic of motion geometry.

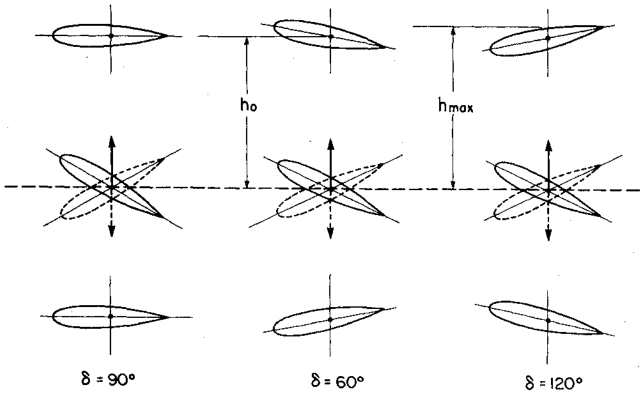

Fig. 3 Wing motions with various phase angles.

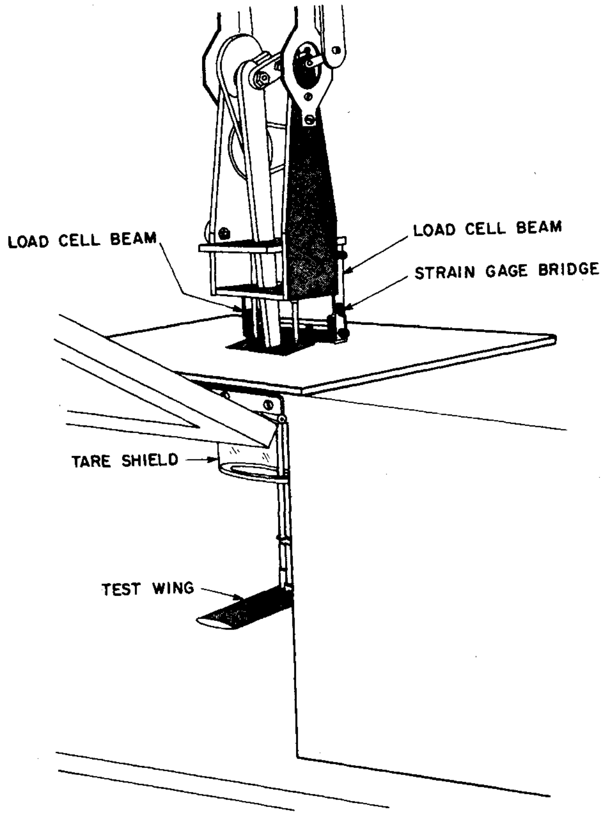

Fig. 4 Oscillation apparatus with wing model.

paper known as "silkspan" and painted with three coats of clear airplane dope, with light sanding between coats. Hence the surface was smooth, but by no means a mirror finish. The static drag measurements (shown in Fig. 7) indicated sufficient roughness to give a turbulent boundary layer.

The motion geometry for the oscillating wing is shown in Fig. 2, where h is vertical displacement of the airfoil's midchord (positive up) and α the geometric angle of attack between the chord line and the mean flow direction. The motion was nearly harmonic and described by

$$h = h_0 \sin \omega t$$

$$\alpha = \alpha_0 \sin(\omega t + \delta)$$

where h_0 and α_0 are the maximum magnitudes of h and α, respectively, ω the oscillation frequency in rad/s, and δ the phase angle between h and α motions. The role of δ is best illustrated by Fig. 3, which shows that at maximum positive h $(h = h_0)$, α has a positive value when $-90 < \delta < 90$ deg and a negative value when $270 > \delta > 90$ deg.

The oscillation apparatus is shown in Figs. 1, 4, and 6. A U-shaped frame supports a small dc electric motor, speed reduction pulleys, and a horizontal shaft. Crank arms are attached to the center and ends of the shaft and are rotated by means of a belt-pulley system connected to the electric motor. The center crank arms drive, through a long connecting rod, a small platform attached to vertical sliding tubes. From the platform, a rigidly attached vertical tube extends to the wing's midchord pivot.

The wing's pitch articulation is provided by a bevel gear attached to the horizontal rotating shaft. This gear drives a vertical shaft which extends through one of the vertical sliding tubes on the small platform to terminate in a conical crank mechanism. As Fig. 1 shows, this conical crank is attached, through a small connecting rod, to a wing-fixed arm. Hence, the wing is oscillated in pitch at the same frequency as the vertical motion. The phase angle between the two motions can be adjusted in 15 deg increments through the relative positioning of the two bevel gears, and the pitch amplitude is determined by the location of the small connecting link in

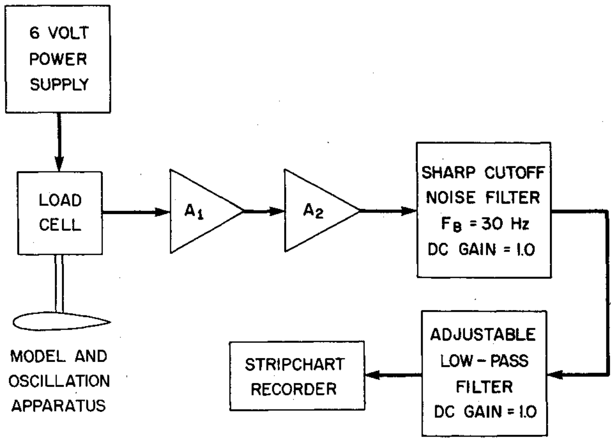

Fig. 5 Schematic of wind-tunnel instrumentation.

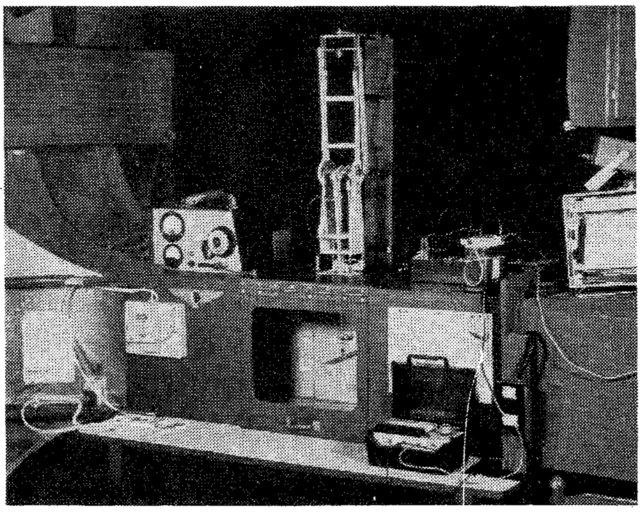

Fig. 6 Overview of test setup.

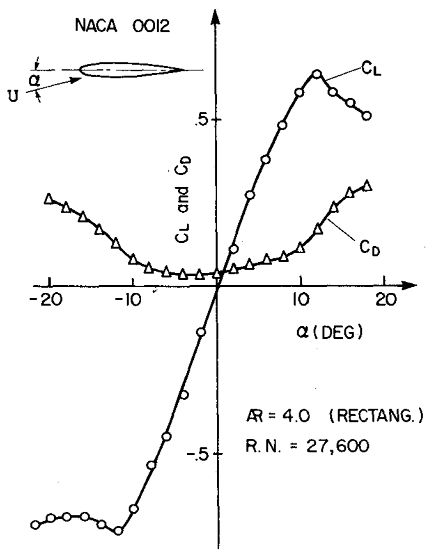

Fig. 7 Wing model's static aerodynamic characteristics.

various pivot holes in the conical-crank arm and wing-fixed arm. The crank arms on the ends of the horizontal rotating shaft are 180 deg displaced from the center arms and they drive, through two long connecting rods, a horizontal bar guided in two vertical slots. Attached to this bar is a mass which statically and dynamically balances the moving components of the system. The pitching of the wing does not allow a "perfect" balance, but this effect is negligible and the system is, for all practical purposes, entirely balanced. This is necessary in order to minimize net unbalanced inertial forces which could obscure the measurement of the relatively small thrust forces.

A counting switch was placed near the top of the rig so that it was tripped once per cycle by the sliding horizontal bar. The signal from this was conditioned by a one-shot circuit (to assure just one pulse per switch actuation) and fed to a Heathkit IM-4100 frequency counter which was used in period mode to get an accurate measurement of the flapping rates.

Thrust is measured with a parallelogram-beam strain gage load cell which is mounted between the top of the test section and the base of the U-shaped support of the oscillation apparatus. This is the apparatus' only exterior mechanical attachment, hence the mean stream direction forces on the wing and its support are entirely measured by the load cell. Since a portion of the long connecting rod and sliding tubes extend into the test section, the tare drag would vary cyclically with the oscillation. This effect was minimized by shielding all but the wing's final support tube in a ceiling-mounted streamlined fairing.

The load measuring instrumentation is diagrammed in Fig. 5. The excitation is provided by a 6 V dc source (a wet cell to avoid powerline transients) and the bridge output signal is fed to A_1, a Philbrick-Nexus model 1701 chopper-stabilized operational amplifier. The second stage amplifier A_2 is a Philbrick SA-1. Both A_1 and A_2 were set to fixed gains of 142, giving an overall voltage gain of 20,300 or 20 mV output per microvolt of the load-cell bridge signal. The objective of this high-gain low-drift instrumentation was to resolve forces of a few thousandths of a pound which were typical of the average thrusting effort generated by the wing. Not unexpectedly, the system required filtering to remove 60 cycle noise. A three-stage sixth-order Butterworth filter with a breakpoint at 30 Hz, a rolloff of 120 dB/decade, and a dc gain of unity served as the primary filter (effectively suppresses 60 Hz hum, but retains fast enough response to observe rapid transients). For the mean thrust measurements sought in this experiment, a second unity-gain filter was added to slow the system down, giving the effect of a heavily damped mechanical balance. This second-stage filter had a breakpoint of 0.3 Hz and a rolloff of 20 dB/decade. The readings were recorded on a Leeds and Northrup XL600 chart recorder, which gave a permanent record of the measurements.

The wind tunnel used for these experiments is a conventional pull-through open-circuit design with a screened and honeycombed straightener, a 9/1 area contraction cone, and a 15 inch square long test section with a 15 inch square cross section. A 3 ft diam, 8-blade fan at the end of the diffuser is driven by a 1½ hp 220 V ac motor. Speed changes are effected with a belt-drive system and quick-change pulleys. Figure 6 shows a portion of the wind tunnel, including the test section with the oscillation apparatus, wing model, and instrumentation.

Test Procedure

As mentioned earlier, the tare drag varied with cyclic position of the oscillation apparatus. Hence, a mean tare drag was obtained by oscillating the wing at 1.7 Hz. It was observed that no significant thrust was produced at this frequency, which is supported by an extrapolation of the results. All thrust readings were taken as changes from the 1.7 Hz baseline.

For all tests, h_0 was fixed at 1.25 in., which gave $2h_0/C=1.25$. Also, for the majority of the runs, the mean wind speed was held constant at 26.1 ft/s, which gave a wing Reynolds number of 27,800. The variable parameters were α_0, δ, and ω with the specific values tested being: $\alpha_0=0$, 5.7,

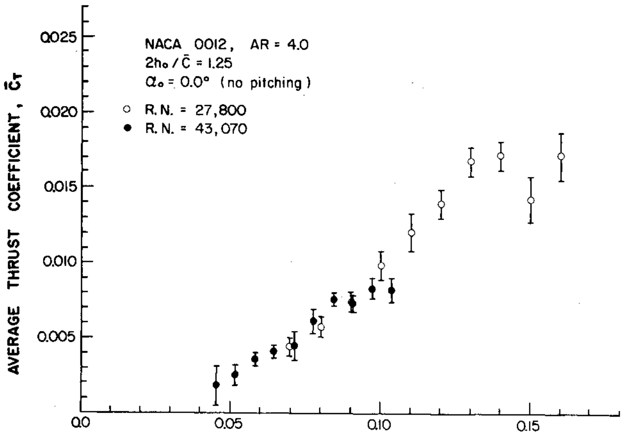

Fig. 8 $\bar{C}_T$ **results for plunging motion only.**

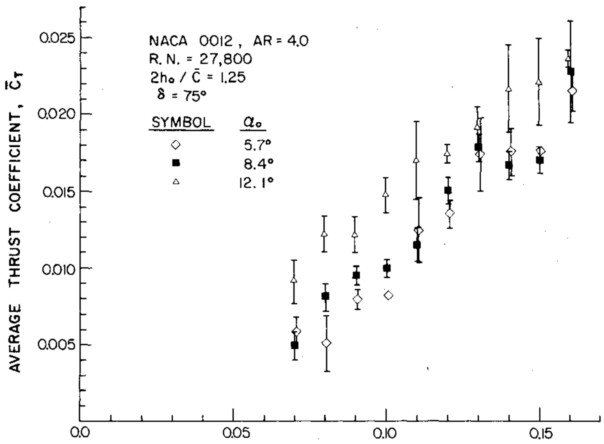

Fig. 10 $\bar{C}_T$ **results for** $\delta = 75$ **deg.**

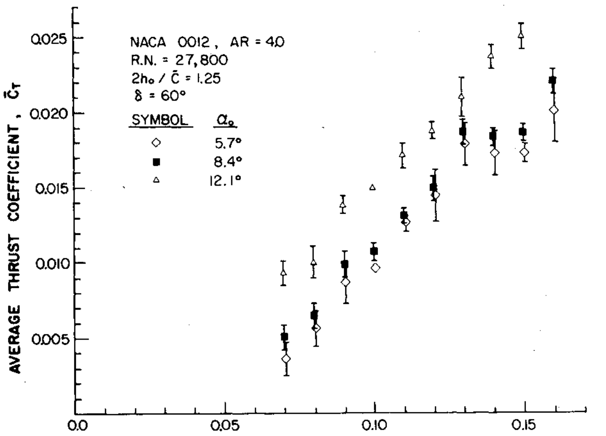

Fig. 9 $\bar{C}_T$ **results for** $\delta = 60$ **deg.**

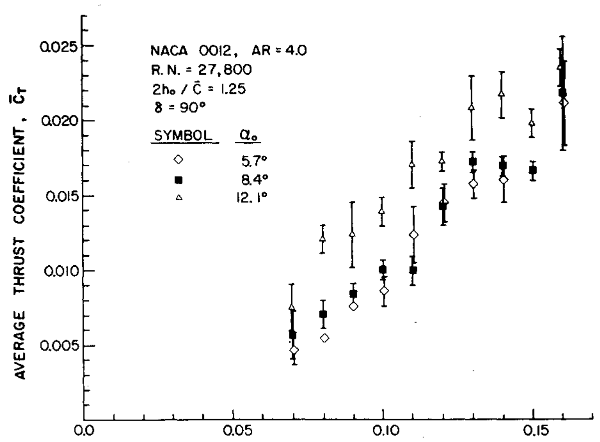

Fig. 11 $\bar{C}_T$ **results for** $\delta = 90$ **deg.**

8.4, and 12.1 deg; $\delta = 60$, 75, 90, 105, and 120 deg; $\omega/2\pi = 3.5$, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0 Hz. The test procedure was to set α_0 and δ and to record thrust signals at the various frequencies. Three consecutive readings were taken for each frequency, separated by return to the 1.7 Hz baseline frequency. Each frequency was held long enough for a steady-state value to be obtained. The chart recorder trace contained a small residual of the wing's oscillation, but the mean value could be readily identified.

Results

The static aerodynamic characteristics of the wing are shown in Fig. 7. The zero-angle value drag coefficient is 0.0407, which compares with 0.0194 for a zero-angle flat plate with a turbulent boundary layer at this Reynolds number (28,000). Although the wing's higher C_D and slightly asymmetric drag curve can be partially ascribed to its pivot and pitch-arm fitting and somewhat textured surface finish, it is still clear that its boundary layer is predominantly turbulent.

The load cell was reoriented for the lift coefficient measurements, which show good linear behavior up to a static-stall angle of about 12 deg. The maximum C_L (≈ 0.7) and mean lift curve slope (3.51/rad) are expected quantities for this Reynolds number and aspect ratio. Therefore, the wing had decent attached flow characteristics over an angle-of-attack range of ≈ -12 to $+12$ deg.

The results of the oscillation tests are given in Figs. 8-13, where k is a nondimensional frequency ("reduced frequency") given by

$$k = \omega C / 2U$$

and $\bar{C}_T$ is a nondimensional mean thrust (thrust coefficient) defined by

$$\bar{C}_T = \frac{\text{Mean thrust}}{[(\rho/2)U^2 S(2h_{\max}/C)^2]}$$

where S is the wing's planform area and $h_{\max}$ is the maximum vertical displacement of the leading edge if $-90 < \delta < 90$ deg or the trailing edge if $90 < \delta < 270$ deg.

For all results, the plotted points are the average of at least three readings and the vertical bars represent the maximum variance of these readings from the mean. For some combinations of the variable parameters the readings were steadier and more consistent than for others, hence the variation in error bar size.

The first tests were for $\alpha_0 = 0$ (no pitching), shown in Fig. 8. For this case, the thrusting can be viewed as due entirely to leading-edge suction, which is generally very sensitive to flow separation in the leading-edge region and, hence, to Reynolds number and surface roughness. The Reynolds number sensitivity was assessed by performing the experiments at 26.1 and 40.5 ft/s which gave Reynolds number values of 27,800 and 43,070, respectively. As seen in Fig. 8, the $\bar{C}_T$ vs k curves overlap nicely, which indicates a low Reynolds number sensitivity for the leading-edge suction force in these particular experiments.

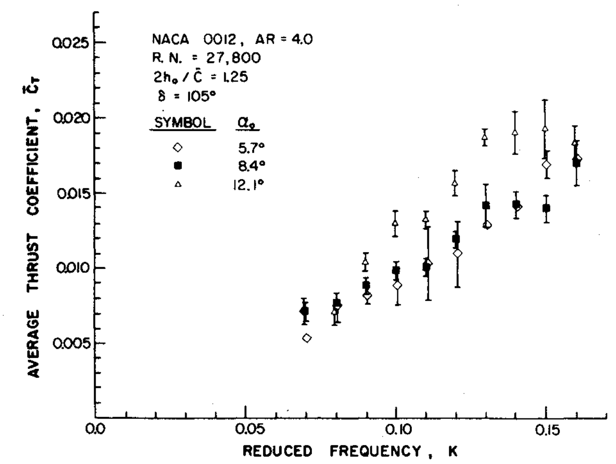

Fig. 12 $\bar{C}_T$ results for $\delta = 105$ deg.

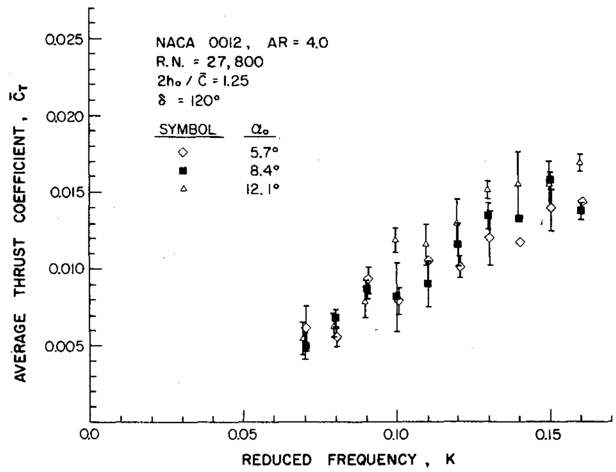

Fig. 13 $\bar{C}_T$ results for $\delta = 120$ deg.

Next, the effect of the leading-edge's geometry was roughly assessed by reversing the wing so that the sharp trailing edge faced windward. The results (not shown here) indicated that essentially no thrust was produced in the reversed orientation and the tare drag increased moderately. Clearly, the wing's leading edge was adequately shaped and finished to generate a significant suction force.

Notice that the $\bar{C}_T$ values increase with k up to $k \approx 0.13$, beyond which point the $\bar{C}_T$ values remain ≈ 0.17. Quasisteady theory from Kuchemann and Weber[8] states that $\bar{C}_T$ should be proportional with k^2, and in fact $\bar{C}_T/k^2 \approx 1.0$ when $k<0.13$, which compares with the theoretical value of 1.40 from Ref. 8. However, unsteady flow effects cause a reduction in $\bar{C}_T/k^2$ when $k>0.13$ in a manner similar to Chopra and Kambe's[9] analysis.

This behavior is even more pronounced in the results with pitch articulation, as shown in Figs. 9-13. $\bar{C}_T$ increases with k, but is not proportional to k^2. In fact, $\bar{C}_T/k^2$ generally decreases with k throughout the entire range of reduced frequencies considered. This is, again, qualitatively consistent with the results of Ref. 9.

With pitch articulation, thrusting can be generated not only by leading-edge suction, but also by the streamwise component of the wing's normal force. Hence, it is not surprising that for certain combinations of δ and α_0 the $\bar{C}_T$ values were considerably greater than for the $\alpha_0 = 0$ case. The largest values were for $\delta = 60$ deg and $\alpha_0 = 12.1$ deg, as seen in Fig. 9. Notice that the differences between the $\alpha_0 = 12.1$ and 8.4 deg cases are, proportionately, much greater than those between the $\alpha_0 = 8.4$ and 5.7 deg cases. This is also generally true for the results at the other phase angles, and shows that $\bar{C}_T$ can vary nonlinearly with α_0 and that large α_0 values may be necessary to generate large $\bar{C}_T$ values.

The results also show a variation with phase angle. Generally, for given α_0 and k, the $\bar{C}_T$ values decrease with increasing δ. However, the variation is not uniform in that the decrease of the values is relatively small from the $\delta = 60$ deg to the 90 deg cases. The decrease is much greater beyond that, with the $\delta = 120$ deg case giving the lowest overall $\bar{C}_T$ values.

With the exception of Scherer,[4] the authors have found no other theoretical studies of oscillating-wing propulsion which have tried to include stall effects, the assumption being made that the flow is fully attached. In order for the experimental results to provide a useful data base for such theories, it is important to assess the degree to which stall occurred in the tests. To do this, the maximum values of the relative angle of attack of the leading edge, $(\alpha_{le})_{max}$ were calculated for each combination of parameters tested. The equation used was

$$\alpha_{le} = \alpha - \dot{h}/U - \dot{\alpha}C/2U$$

and the maximum value for all cases was 11.5 deg when $\alpha_0 = 0$ and frequency = 8.0 Hz. Within the range of reduced frequencies tested, McKinney and DeLaurier[10] showed that stall may be delayed to angles considerably higher than the static value. Since in fact $(\alpha_{le})_{max}$ is slightly less than the measured static-stall angle of 12 deg, it may be concluded that the wing was unstalled for all experimental conditions.

Finally, an attempt was made to measure propulsive efficiency. As other authors have noted,[4,7-9] high $\bar{C}_T$ values alone are not sufficient to insure the usefulness of an oscillating-wing propulsor; these values must be accompanied with reasonable propulsive efficiencies, $\bar{\eta}$, as defined by

$$\bar{\eta} = \frac{(\text{Mean thrust}) \times U}{\text{Mean power in}}$$

where "Mean power in" is the value absorbed by the wing's aerodynamic forces and moments during the oscillation. This was found by measuring the electrical power necessary to oscillate the entire rig plus wing and subtracting from that the power necessary to oscillate the rig with the wing replaced by a concentrated mass. Unfortunately, the power absorbed by the rig significantly outweighed that absorbed by the wing. Hence the differences between the wing-on and wing-off values were difficult to measure accurately. This is due mainly to the friction of the sliding tubes in the mechanism, and the authors think that a relatively simple redesign utilizing linear antifriction bearings could reduce this significantly. $\bar{\eta}$ measurements will therefore be the subject of a future paper. By way of preliminary results, however, for the $\alpha_0 = 0$ and $U = 26.1$ ft/s case, $\bar{\eta}$ appeared to vary from ≈ 0.50 at 3.5 Hz to ≈ 0.15 at 8.0 Hz.

Conclusion

The purpose of this work has been to obtain oscillating-wing thrusts of sufficient accuracy and parameter range so as to serve as a data base for subsequent theoretical comparisons. Such information has been scarce, in comparison with analytical studies, because of the difficulty of designing an experimental rig whose unbalanced inertial forces do not obscure the relatively small thrust values. One solution to this is the apparatus described here. Its performance has been very satisfactory for measuring average thrusts, and it should also be a workable configuration at larger scales. The only specific design change would be the substitution of linear ball bearings in the sliding parts to reduce tare power and to keep it more constant throughout the experiment (reducing dependence on break-in time and degree of lubrication). This should enable accurate propulsive efficiency measurements to be made as described earlier.

In summary, although the small scale of the experiment limited the results to relatively low Reynolds numbers, the wing's static aerodynamic characteristics were well behaved and indicative of attached flow up to α magnitudes of ≈ 12 deg. Also, the oscillatory measurements showed that average thrust may increase considerably with pitch amplitude α_0 and that phase angles δ from 90 to 60 deg gave significantly higher average thrusts than those from 90 to 120 deg.

Further, the $\alpha_0 = 0$ tests show the importance of leading-edge suction in thrust production and how this is affected by leading-edge geometry, i.e., that too sharp a leading edge can considerably reduce or eliminate the suction force. The quasisteady theories of Refs. 6-8 explain $\alpha_0 = 0$ thrust production by means of a "tilting" lift vector which, by being always perpendicular to the relative wind vector, can give a thrust component parallel to the mean stream direction. Such an analytical model can obscure the role of leading-edge suction which is that portion of an airfoil's net pressure distribution giving a chordwise force, the remainder giving a force normal to the chord.

Future work will include measurements of propulsive efficiencies which, along with the thrust results in this paper, should give realistic insights into oscillating-wing propulsion. Certain animals, such as whales and porpoises, appear to propel themselves with considerable efficiency by oscillating their tails in a fashion similar to that of the wing in these tests. Further experiments should help to quantify this and assess the possibility—and desirability—of the practical utilization of a mechanical oscillating-wing propulsor.

Acknowledgments

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