Arch. Mech., 38, 5-6, pp. 577-584, Warszawa 1986

Direct measurements of hydrodynamic forces on a flapping wing(*)

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THIS WORK presents results of an experimental investigation of the forces exerted by water flowing around an oscillating wing for a variety of parameters defining the movement of the obstacle. Special care was taken in order to achieve precise and reproductible results. This investigation was prompted by the need of more accurate results necessary to validate new theoretical and numerical models as well as by the desire of mechanically reproducing, in a bionic way and thanks to available new technologies, the movements of aquatic or aerial animals.

W pracy przedstawiono wyniki badań doświadczalnych dotyczących sił wywieranych przez strumień wody opływający oscylujące skrzydło przy różnych wartościach parametrów charakteryzujących jego ruch. Szczególną wagę przykłada się do uzyskania możliwie ścisłych i odtwarzalnych wyników. Badania wynikają z potrzeby otrzymania ściślejszych danych umożliwiających weryfikację nowych modeli teoretycznych i numerycznych omawianego zjawiska w związku z postępami bioniki dotyczącymi ruchu stworzeń latających i pływających.

В работе представлены результаты экспериментальных исследований, касающиеся сил оказываемых потоком воды обтекающим осциллирующее крыло, при разных значениях параметров, характеризующих его движение. Особенное внимание уделяется получению возможно точных и воспроизводимых результатов. Исследования вытекают из необходимости получения более точных данных, дающих возможность проверить новые теоретические и численные модели обсуждаемого явления, в связи с прогрессом бионики, касающимся движения летающих и плавающих существ.

1. Introduction

THIS WORK presents results of an experimental investigation of the instantaneous forces induced by water flowing around an oscillating wing.

A double motive led us to carry out this investigation. On the one hand, the validation of new theoretical and numerical models requires more accurate experimental results. On the other hand, the exceptional performances of a large number of animals in their aquatic or aerial movements prompted us to reproduce those movements in a bionic way with the use of modern technology.

Most of the recent experiments in this field deal with small Reynolds numbers or reduced frequencies. Furthermore, since tests are generally performed in the air, inertial forces play a larger part than the aerodynamic forces, thus greatly diminishing the precision of the measurements [1–2].

The following results concern the simple harmonic motion around the upstream quarter chord of a NACA 0012 wing model. The total amplitudes stay small (16°) as do the mean

(*) Paper given at XVIII Symposium on Advanced Problems and Methods in Fluid Mechanics. Sobieszewo, 2–6 September 1985.

incidences. Oscillation frequencies ranging from 1 to 6 Hz lead to reduced frequencies varying from 0.2 to 1.2 in a 2 m/s water flow (Re = 240.000).

Experimental values of the lift force, drag force and instantaneous moment are compared with the corresponding ones deduced from two simple theories developed by: SEARS [3] and COUCHET–ROUCOUS [4].

2. Methods and materials

The wing model is made of altuglass to minimize inertia. The profile (NACA 0012) extends on the full tunnel width. It is composed of three different parts: two non-weighed side guard profiles identical with a central part on which a three-component extensometer

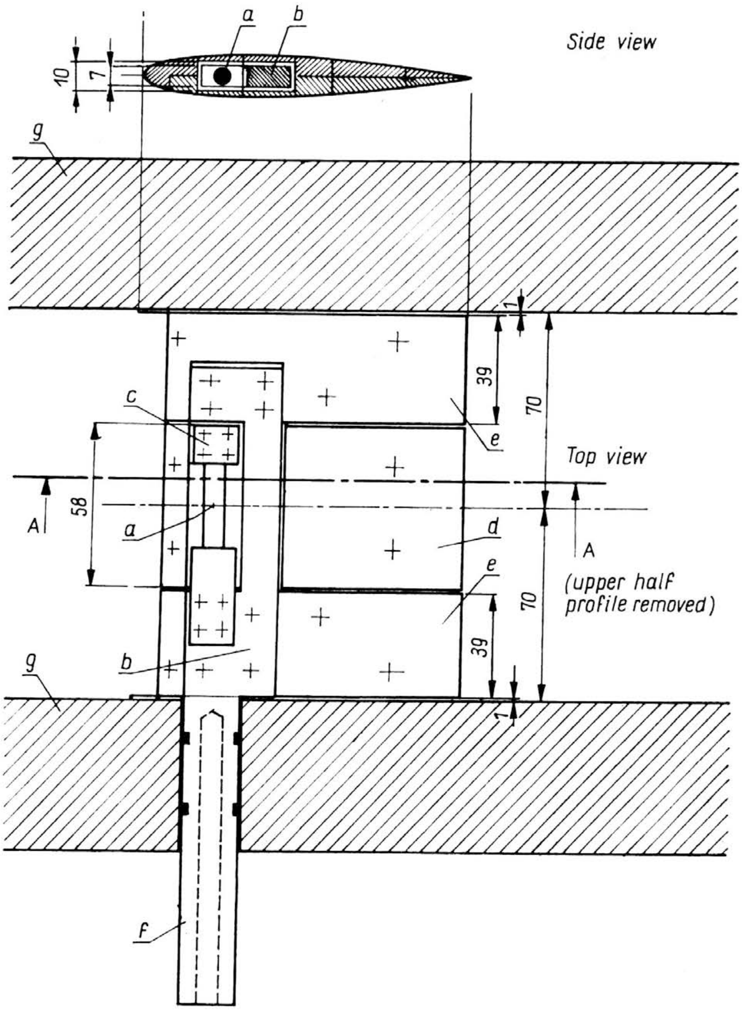

FIG. 1.a) Extensometric arm, b) balance skeleton, c) platina for the model anchoring d) lower half profile weighed part, e) side guard profiles, f) oscillation axis, g) walls of the fluid tunnel.

is connected. The resonance frequency of the wing arm system is 140 Hz. Figure 1 shows the principal parts of the model.

The oscillating motion is generated through a crank-arm system driven by a variable speed motor. The profile position is located through a rotary potentiometer fed by direct current. A synchronization top triggers the simultaneous acquisition of the three balance signals and of the position signal. Fifty cycles are stored in four numerical memories of 256 channels each. The sample period is adjusted to the movement period. Taking into account the standard matrix of the balance, a computer program analyses the results and brings out the dimensionless forces with respect to a coordinate system moving with the flow.

The reproducibility of the results and the negligible influence of inertial effects has been verified by carrying out the same type of movement in calm air. The balance zeros are reset before each test sequences. The zero incidence is determined by the zero of the lift force.

3. Results and discussion

The theoretical model developed by Sears uses the thin profile theory. It also assumes the fluid to be non-viscous and the movement orthogonal to U_∞ to be negligible. For a simple harmonic motion: $\theta = \theta_0 e^{i\omega t}$. Sears derives the unsteady lift force as a three-term summation.

$$Cz = Cz_0 + Cz_1 + Cz_2 \quad \text{where} \quad Cz_0 = 2\Pi\theta C(k); \quad Cz_1 = \frac{2\Pi c}{u_\infty}\dot{\theta}\left[C(k) + \frac{1}{4}\right],$$

$$Cz_2 = -\frac{\Pi c^2 \ddot{\theta}}{8u_\infty^2},$$

c is the profile chord and $C(k)$ a complex function of the reduced frequency $k = \dfrac{\omega c}{2u_\infty}$.

The moment coefficient takes the following form:

$$C_m = -\frac{\Pi}{4}\left[\frac{c\dot{\theta}}{u_\infty} + \frac{3c^2\ddot{\theta}}{16u_\infty^2}\right].$$

This coefficient does not depend on $C(k)$.

The drag forces are automatically equal to zero.

For an identical movement, under the nonviscous fluid assumption, Couchet carries out a conformal transformation method. The profile is compared to a plane plate with a $4a$ length. The calculation does not consider the wake effect "tangential-rotational". The Couchet theory leads to the following results:

$$C_z = \frac{2\Pi}{u_\infty^2}\left[(-u_\infty(m+a\omega) - a^2\omega^2 \sin\theta(t) - a\frac{dm}{dt}\cos\theta(t))\right],$$

$$C_x = \frac{2\Pi}{u_\infty^2}\left[-a^2\omega^2\cos\theta(t) + a\frac{dm}{dt}\sin\theta(t)\right],$$

$$C_m = -\frac{\Pi}{u_\infty^2}\left[ml - \frac{a^2}{2}\frac{d\omega}{dt}\right],$$

where l and m are the velocity components of the middle of the plate moving with a $\theta(t)$ movement in the resting fluid. Figures 2 and 3 concern a harmonic oscillating movement ranging from $-8°$ to $+8°$. The incidence is equal to zero at $t = 0$, then becomes negative. Figure 2a shows the variation in the lift force coefficient over one period of time for

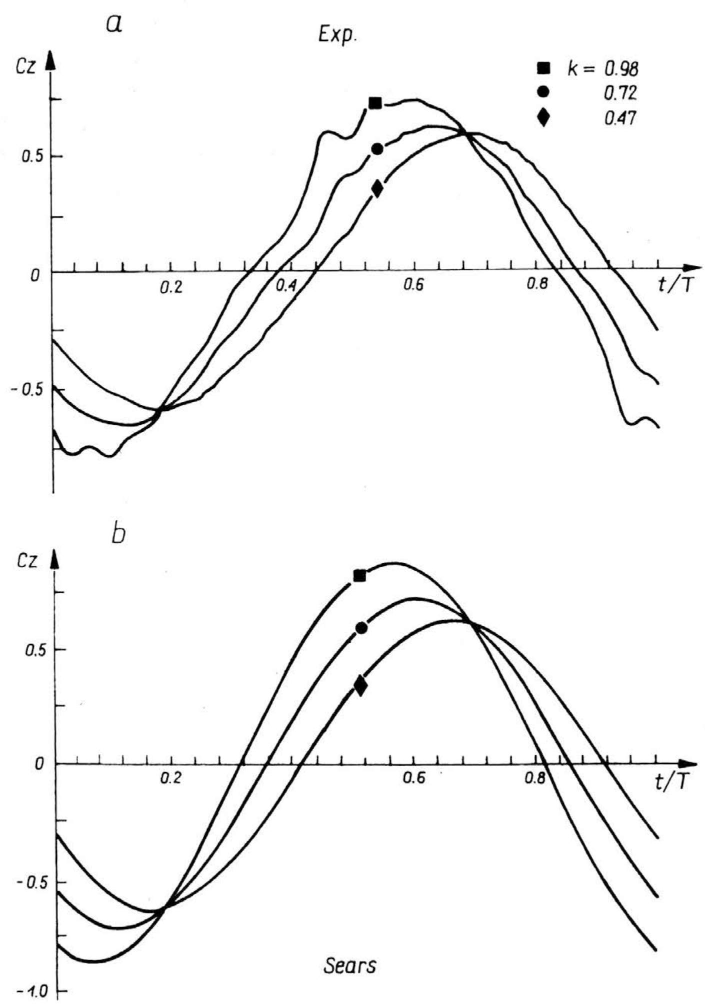

FIG. 2.a) Experimental values of the lift force calculated for three different reduced frequencies (k), over one period of time (movement ranging from $-8°$ to $+8°$), b) Theoretical values derivated from Sears (same movement and same reduced frequencies).

three different reduced frequency values. Figure 2b gives the Cz variation, calculated from the Sears theory, for the same reduced frequencies.

The values derived from the "tangential-rotational" approximation are added to the viscous contributions deduced from the steady measurements of the drag force, leading to the theoretical drag force (Fig. 3b). These results are to be compared with the experimental drag forces (Fig. 3a). Here again, one can notice the similar aspect of the curves

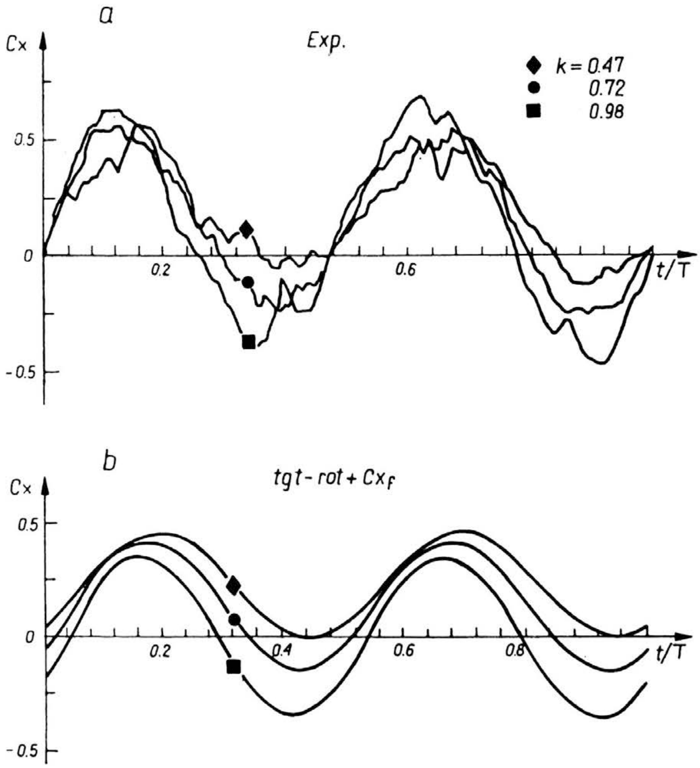

FIG. 3.a) Experimental curves of the drag force calculated over one period of time for three different reduced frequencies b) "Semi-theoretical" curves. Same movement and reduced frequencies.

although the "semi-theoretical" amplitudes of Fig. 3b appear to be quite smaller than the experimental ones.

The same type of comparison as before is done in Figs. 4a and 4b for a movement ranging from 0° to 16°.

By the drag coefficient in the experimental case, one can notice a larger variation of the amplitude as a function of k. The real fluid effects are very sensitive here, especially when the oscillation frequency is small, because the hydrodynamic stalling cannot be avoided.

Figure 5 shows a global comparative evaluation between theory and experiments. The curves represent the angles of phase advance for the lift forces versus the movement and the ratios of the maximal lift force amplitude to the equivalent "quasi-steady" amplitude as functions of the reduced frequency k.

The comparison between the theoretical lift force phase leads and the experimental data shows good agreement. For amplitudes, only results of the movement ranging from $-8°$ to $+8°$ are close to the theoretical calculation developed by Sears. The oscillations ranging from $-16°$ to 0° and from 0° to $+16°$ lead to discrepancies of instantaneous lift forces about 1.3 times those obtained by a theoretical quasi-stationary evaluation. Such large amplitude differences have been already observed during an experimental work on flying insects in a wind tunnel [5].

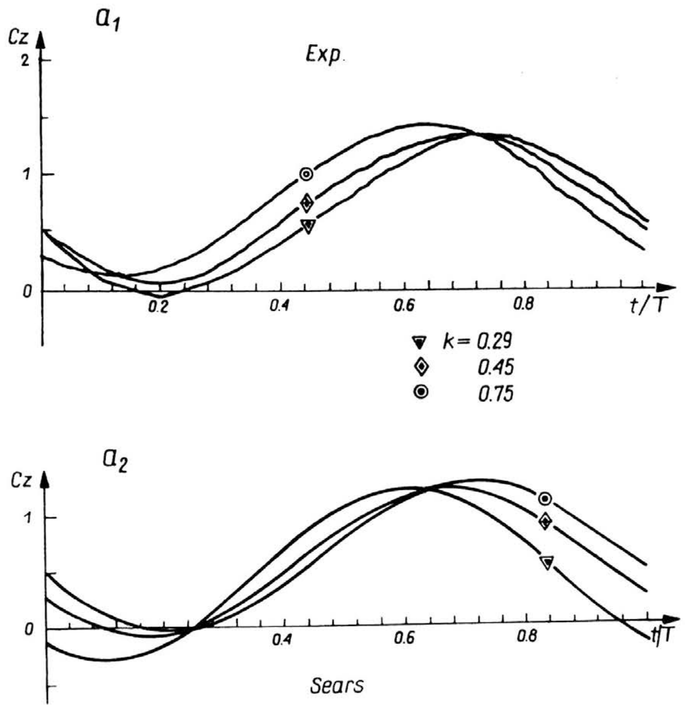

FIG. 4.a) Comparison of experimental and theoretical instantaneous lift force coefficient calculated over one cycle for various reduced frequencies.

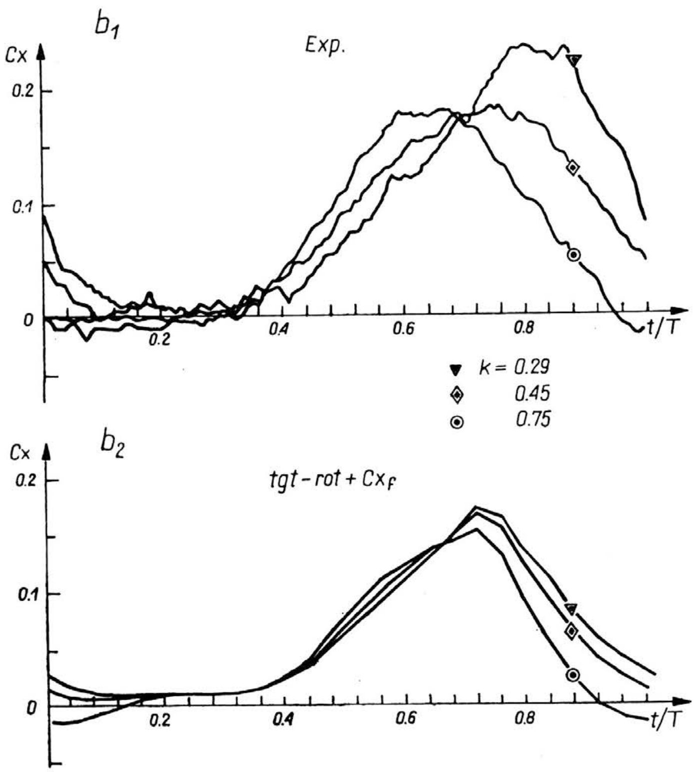

FIG. 4.b) Comparison of experimental and theoretical instantaneous drag force coefficient calculated over one cycle for various reduced frequencies.

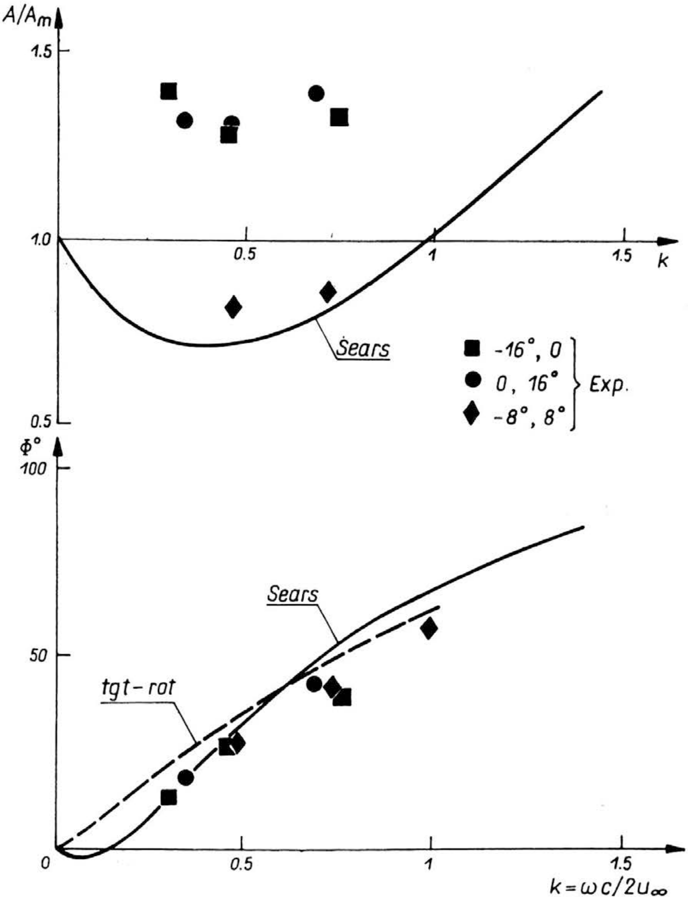

FIG. 5. Lift forces, Upper graph: y-axis: A/A_m ratio of the maximal amplitude to the equivalent quasi tationary amplitude. Lower graph: y-axis: Φ angle of phase advance of the lift forces upon the movement. Both graphs: X-axis: k, reduced frequency.

4. Conclusion

We now have at our disposal a fast and reliable experimental apparatus which enables us to determine the instantaneous forces generated by a moving profile. Although the preceding comparisons are carried out for relatively small oscillating amplitudes and reduced frequencies, they point out the existence of gaps in the simple theoretical models. Nevertheless, these models can be used as a primary tool for the optimization of a propulsive or lifting movement. Presently the experimental study continues with more complex types of movement, such as nonsymetrical and associating rotative motion with translation.

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Received November 22, 1985.