Technical Notes

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Lift Response of a Rectangular Wing Undergoing a Step Change in Forward Speed

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Introduction

WITH increasing emphasis being placed on the maneuverability of advanced fighter designs, aerodynamicists are facing the challenge of predicting the unsteady loads encountered by such aircraft. One standard technique that is often utilized is a two-dimensional analysis first proposed by von Kármán and Sears in 1938.[1] This technique employed an integral approach to account for changes in loading due to vorticity shed into the wake of an airfoil. This integral itself, however, is dependent upon the indicial response function of an airfoil, derived in 1925 by Wagner.[2] Wagner's result characterized the normalized lift response of an airfoil due to a step change in downwash, the step response of the airfoil. Such functions were derived in 1939 by Jones[3] to account for wings of finite aspect ratio and reformulated by Dore[4] in 1964.

It is seemingly curious that these indicial response functions, the heart of such widely used analyses, have not been directly verified. The results presented here are the culmination of an effort to determine experimentally such functions by approximating a step change in forward speed seen by a finite wing.

Experimental Setup

Tests were performed on a 9-in. chord, 36-in. span (aspect ratio 4) balsa wood and Mono-Kote wing at a nominal angle of attack of 10 deg. The wing was secured to two piezoquartz force transducers that were in turn attached to a pylon. This pylon was mounted to an aluminum plate cart with four linear bearings attached to its underside. These bearings ran along two parallel precision ground steel rails bolted to a heavy steel table.

Motive force was supplied by a large bore, short stroke air cylinder also connected to the table. This adjustable system allowed, for example, the cart to be accelerated to 35 ft/s in 3 in. of travel. The cart motion was arrested by using a pneumatically operated disk brake caliper. The test stand is shown in Fig. 1.

Two data records were simultaneously recorded using a Nicolet 3091 digital oscilloscope. The output from the force transducers was passed through a 200-Hz low-pass filter, then recorded. Position data were acquired from a cart-mounted photodiode that rode along a table-mounted optical encoder rail. Both records were transferred to a microcomputer for postprocessing.

In practice, an air cylinder pressure was determined for the desired cart speed, then held constant throughout the test runs. The cart was restrained while the cylinder was charged to the needed pressure. After all data acquisition equipment was readied, the trigger was released, and the cart blasted down the rails. A number of similar runs with the wing in place were taken and then ensemble averaged. A second group of runs were acquired with a weight equal to that of the wing on the transducers. These runs were also ensemble averaged. This second average was considered a tare and was simply subtracted from the average of the wing runs.

Data acquisition consisted of performing a least-squares fit on the position vs time data. This allowed a straightforward

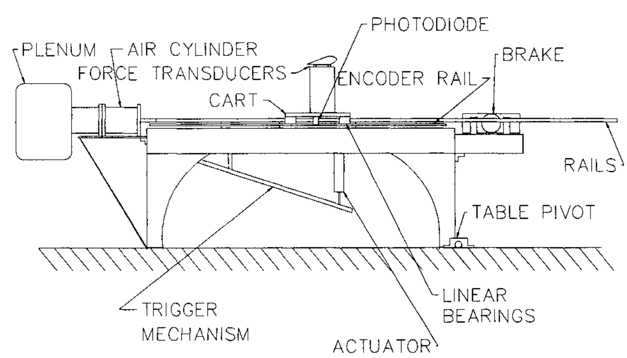

Fig. 1 Experimental setup.

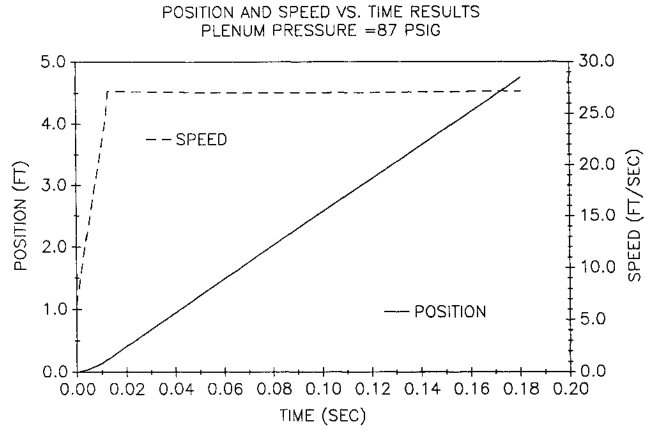

Fig. 2 Position and speed vs time results for aspect ratio 4 wing test.

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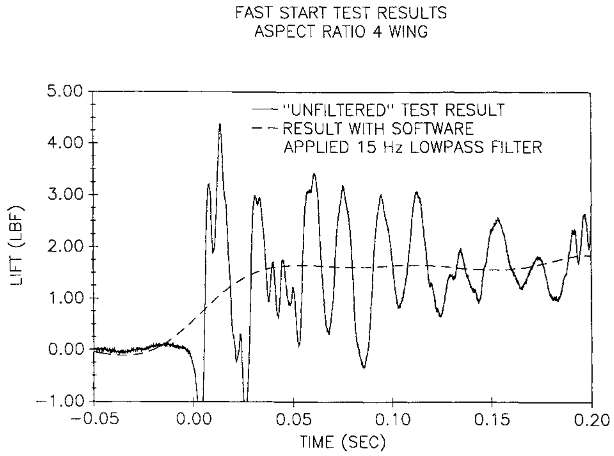

Fig. 3 Experimental force vs time results for aspect ratio 4 wing test, showing "unfiltered" and software filtered results.

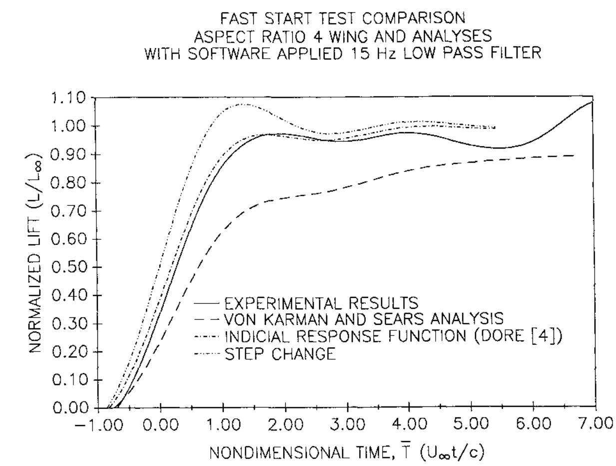

Fig. 4 Nondimensional lift vs nondimensional time results for the aspect ratio 4 wing test, showing software filtered experimental, analytical, and step-change results.

calculation of speed or acceleration vs time to be made. The voltage record corresponding to the force data, treated as just outlined, was multiplied at each recorded point by the transducer gain, yielding force as a function of time. Further details can be found in Sawyer.[5]

Results and Analysis

Position and speed vs time results for the force data presented here are shown in Fig. 2. An approximation of a step change in speed is desired, and it is seen that the wing reaches its steady-state speed of 27.1 ft/s in about 0.013 s. This speed value stays constant (within 1%) for the remainder of the wing travel. The recorded force is shown in Fig. 3, labeled as the "unfiltered" test result.

Two observations are readily apparent. First, the response is dominated by large amplitude oscillations. Given that for the most part the actual lift was expected to be a monotonic increase (e.g., following an indicial response function), it was concluded that these oscillations were not caused by aerodynamic forces. This force result was treated with a fast Fourier transform (FFT) routine to reveal the dominant frequencies. Impulse testing of the test rig revealed the frequencies of the dominant structural modes. These modes were readily matched with the frequencies encountered in the force data. Thus when the cart was accelerated, the structural modes were excited, adding "noise" to the force data.

It was felt that even in the presence of this noise, some useful information about the lift could be gained. To this end a software filtering scheme was devised that could treat the force data a posteriori. Since the lowest identifiable structural modes occurred at 22 and 52 Hz, the data were treated with a 15-Hz low-pass software filter. This result is also shown in Fig. 3.

A rapid rise in lift to an approximately constant value (L_∞) of 1.6 lbf (lift coefficient $C_L = 0.83$) is seen. When given the geometry of the test and the final speed, a flat plate vortex lattice code predicted L_∞ to be 1.46 lbf ($C_L = 0.76$), a difference of about 9.5%. Given the uncertainty in measuring the angle of attack and that the angle of zero lift was not accounted for, the agreement is considered good. It is however the rate of rise that is of most interest.

Such unsteady results are usually expressed as nondimensional lift (lift L at some time t divided by L_∞) vs a nondimensional time ($\bar{T}$). (Dimensional time t multiplied by the steady-state speed and divided by the wing chord length.) The experimental results can quickly be expressed in this form.

This can be compared with two analyses: the indicial response function of an aspect ratio 4 wing even though the actual motion is not a true step change, and a von Kármán and Sears method that accounts for the actual recorded speed vs time history, but is for a two-dimensional airfoil. Since it was realized that the 15-Hz filter significantly altered temporal content, the two analyses were also passed through the software filter before comparing with the experimental result. The results are shown in Fig. 4.

The agreement between the experimental result and the indicial response function for the aspect ratio 4 wing is striking, both rising to the steady state in a nearly identical manner. As was predicted by Jones[3] and Dore,[4] the finite wing responds to this motion more quickly than an infinite wing (airfoil) modeled by the von Kármán and Sears analysis.

It was feared that the agreement seen was forced by the rise time of the 15-Hz filter. To test this, a step change in lift ($L/L_\infty = 0$, $\bar{T} \leq 0$, $L/L_\infty = 1$, $\bar{T} > 0$) was subjected to the same filtering scheme. The result, also plotted in Fig. 4, showed a much faster rise than any pevious curve. It was concluded then that the other results were rising with a true characteristic of the aerodynamic response.

Conclusions

The result presented showed the response of an aspect ratio 4 rectangular wing to a rapid acceleration to a constant speed. The wing showed the correct steady-state lift, and when the result was filtered to eliminate unwanted noise, it was matched nearly perfectly by the step response for an aspect ratio 4 wing treated by the same filter. The finite size and influence of the rectangular wing wake then is correctly accounted for by theory. This finding is extremely important since an old analysis has finally been verified by experiment.

References

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