

# Technical Notes

## Theodorsen's and Garrick's Flutter Calculations: Revisited

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### Nomenclature

|                |   |                                                                                             |
|----------------|---|---------------------------------------------------------------------------------------------|
| $a$            | = | nondimensional distance from midchord to elastic axis (e.a.), positive aft                  |
| $b$            | = | semichord, ft                                                                               |
| $C(k)$         | = | Theodorsen's circulation function, function of reduced frequency                            |
| $c$            | = | nondimensional distance from midchord to aileron hinge, positive aft                        |
| $F$            | = | nondimensional flutter factor, $\sqrt{\kappa}v_f/b\omega_r r_r$                             |
| $g_h$          | = | structural damping coefficient for flexure mode                                             |
| $g_a$          | = | structural damping coefficient for torsion mode                                             |
| $g_\beta$      | = | structural damping coefficient for aileron deflection mode                                  |
| $h$            | = | vertical deflection, or flexure, degree of freedom, positive down                           |
| $k$            | = | reduced frequency, $\omega b/v$                                                             |
| $k_f$          | = | flutter reduced frequency, $\omega_f b/v_f$                                                 |
| $M$            | = | mass of wing per unit length                                                                |
| $r_r$          | = | nondimensional reference length                                                             |
| $r_a$          | = | nondimensional radius of gyration of wing-aileron, referred to $a$                          |
| $r_\beta$      | = | reduced radius of gyration of aileron, referred to $c$                                      |
| $v$            | = | velocity, fps                                                                               |
| $v_f$          | = | flutter velocity, fps                                                                       |
| $x_a$          | = | nondimensional distance from e.a. to center of gravity (c.g.) of wing-aileron, positive aft |
| $x_\beta$      | = | nondimensional distance from aileron hinge to c.g. of aileron, positive aft                 |
| $\alpha$       | = | torsion degree of freedom, positive leading-edge up                                         |
| $\beta$        | = | aileron-deflection degree of freedom, positive trailing edge down with respect to wing      |
| $\kappa$       | = | mass ratio, $\pi\rho b^2/M$                                                                 |
| $\xi$          | = | partial-span aileron coefficient                                                            |
| $\rho$         | = | mass of air per unit volume                                                                 |
| $\omega$       | = | circular frequency, rad per s (rps)                                                         |
| $\omega_f$     | = | flutter frequency, rps                                                                      |
| $\omega_h$     | = | natural frequency of wing-flexure mode, rps                                                 |
| $\omega_r$     | = | reference frequency, rps                                                                    |
| $\omega_a$     | = | natural frequency of wing-torsion mode, rps                                                 |
| $\omega_\beta$ | = | natural frequency of aileron-deflection mode, rps                                           |

### I. Introduction

NINETY years ago, Theodore Theodorsen was the first to solve the flutter<sup>†</sup> problem in closed form. He published his result in a groundbreaking National Advisory Committee for Aeronautics (NACA) report [1], referred to hereinafter as “NACA 496.” Six and eight years later, with I.E. Garrick as his coauthor, Theodorsen wrote follow-up NACA reports, [2,3] (“NACA 685” and “NACA 741”, respectively), which progressively simplified the solution method and provided many numerical examples in plot form. These three NACA reports will be referred to as Theodorsen's and Garrick's trilogy.

In the year 2000, in an Engineering Note [4], Zeiler pointed out that errors exist in some of the plots in NACA 685 and NACA 741 and that some of those incorrect plots were duplicated in vintage aeroelasticity texts, [5,6]. Zeiler recommended that “... all the plots in these classic and historically important NACA documents be recomputed and published. Such an undertaking would serve two purposes: it would provide numerically correct results for others to use as check cases, and it would bring a sense of closure to the groundbreaking work done by Theodore Theodorsen and I. E. Garrick.”

The purpose of this Technical Note is to make known the existence of three NASA Technical Papers (TPs) that follow Zeiler's recommendation: The first NASA TP, [7], recomputes and replots (and, in many cases, corrects) all flutter results in NACA 496; the second NASA TP, [8], all flutter results in NACA 685; and the third NASA TP, [9], all flutter results in NACA 741. (All three TPs are available on the NASA Technical Report Server, [ntrs.nasa.gov](https://ntrs.nasa.gov).) It is hoped that these three NASATPs provide the sense of closure that Zeiler sought.

Zeiler further stated in his Engineering Note: “One does not set about lightly to correct the masters...” Embracing this notion, the recomputations contained in the three NASA TPs were carefully checked and rechecked, and then checked again using independent flutter solution methods (the  $k$ -method, [10], and  $p$ -method, [11]). In all cases, including those where the original and present recomputed results differed significantly, the independent results were in excellent agreement with the recomputed results, giving confidence in the recomputed results.

### II. Theodorsen's and Garrick's Groundbreaking Trilogy of NACA Reports

Theodorsen's and Garrick's (T&G's) trilogy of papers on aeroelastic flutter, NACA 496, NACA 685, and NACA 741, address a typical section with three degrees of freedom (3DOF): torsion ( $\alpha$ ); aileron deflection ( $\beta$ ); and vertical deflection, or flexure ( $h$ ) in unsteady incompressible flow. Figure 1 is from NACA 741 and illustrates these degrees of freedom, their positive senses, geometric parameters, and inertial entities associated with the typical section. The typical section extends in the  $x$  direction from  $-b$  to  $b$  and the quantities identified in the figure ( $a$ ,  $c$ ,  $r_a^2$ ,  $r_\beta^2$ ,  $x_a$ , and  $x_\beta$ ) are normalized quantities.

Theodorsen's equations [Ref. 1, Eqs. (A), (B), and (C)] define the sum of the moments about the elastic axis, the sum of the moments about the aileron hinge, and the sum of the forces on the entire “wing” in the vertical direction. The equations are comprised of structural and aerodynamic terms and are written as three simultaneous second-order differential equations in the three unknowns  $\alpha$ ,  $\beta$ , and  $h$ . Unsteady circulatory aerodynamics are present in the equations in the form of Theodorsen's circulation function,  $C(k)$ . The right-hand side of each equation is zero.

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<sup>†</sup>As used in this Note, “flutter” is any condition of zero aeroelastic damping. It includes traditional flutter modes as well as the destabilizing and restabilizing extremes of hump modes.

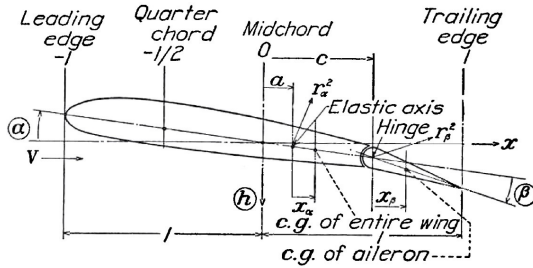


Fig. 1 Sketch illustrating degrees of freedom, their positive senses, and geometric parameters of the typical section, from Ref. [3]. c.g. = center of gravity.

These equations are Fourier transformed from the time domain to the frequency domain, resulting in three simultaneous algebraic equations with complex coefficients. The determinant of these equations is obtained, set equal to zero, and separated into its real and imaginary parts, producing a “real” equation and an “imaginary” equation.

Within the trilogy of papers, the manner of solving the real and imaginary equations for flutter velocity  $v_f$  and flutter reduced frequency  $k_f$  differs from paper to paper, but each requires successive calculations over a range of values of the inverse of reduced frequency,  $1/k$ . Ultimately, three different solution methods are constructed, all of which produce the same, correct, answers, with each successive solution method more straightforward and easier to implement than its predecessor method. References [1–3] do not reveal the ranges in  $1/k$  that were employed in their respective flutter solutions, the increments in  $1/k$ , nor the increments in the abscissa quantity in their flutter boundaries.

#### A. NACA 496 [1]

NACA 496 presents and employs one method specifically for the solution of the two-degrees-of-freedom (2DOF) flutter problem (referred to herein as Solution Method 1) and outlines, but does not employ, a second method for the solution of the three-degrees-of-freedom (3DOF) flutter problem (Solution Method 2, which may also be used to solve the 2DOF flutter problem). Solution Method 1 is ingenious, but complicated, making use of substitution to solve the equations for  $v_f$  and  $k_f$ . NACA 496 contains 11 flutter boundaries computed using Solution Method 1, all for 2DOF.

#### B. NACA 685 [2]

NACA 685 introduces into the equations structural damping (see, e.g., Ref. 5, pp. 560–561) and what it calls a “coupling factor” that attenuates aileron effectiveness and is meant to approximate the effects of a partial-span aileron on a real wing. NACA 685 employs Solution Method 2 to solve both 2DOF and 3DOF flutter problems. In Solution Method 2, simpler and more straightforward than Solution Method 1, the real and imaginary equations are solved simultaneously to obtain  $v_f$  and  $k_f$ . NACA 685 contains over 180 flutter boundaries in its 11 figures and three graphs. The figures contain flutter boundaries for both 2DOF and 3DOF problems. The graphs contain flutter boundaries for 2DOF flutter problems only.

#### C. NACA 741 [3]

NACA 741 also includes structural damping and the coupling factor (that is now referred to as the “partial-span aileron coefficient”). NACA 741 introduces and employs Solution Method 3 to solve only 3DOF flutter problems. Solution Method 3 starts from Solution Method 2 but uses a method of elimination to reduce the order of the real and imaginary equations to first order, thereby simplifying the solution further. NACA 741 contains over 170 flutter boundaries in its 40 figures.

### III. Errors in NACA Reports

Zeiler [4] identified incorrect flutter boundaries in T&G’s NACA reports [2,3]; the present author [7] identified incorrect flutter

boundaries in [1]. Assuming T&G’s equations are correct, potential sources of underlying errors contributing to incorrect flutter boundaries in [1–3] are:

- 1) errors in the input numerical values of quantities employed by T&G in their computations (e.g., inputting  $x_a = 0.2$  when  $x_a = 0.1$  was the intent);
- 2) errors in the tabular values of T&G’s aerodynamic forces in [1,2];
- 3) errors in performing any of the multiple steps in the various solution methods;
- 4) errors as a result of performing the computations at an insufficient number of values of a) the inverse of reduced frequency, and/or b) the abscissa quantity in a plot; and
- 5) errors in plotting the results.

In the example comparisons that follow, the present author reasons that Error Sources 1, 4, and 5 were the primary causes of some of T&G’s incorrect flutter boundaries.

Regarding potential Error Source 2, in [7], the present author revealed an error in Theodorsen’s tabular values of  $R''_{ah}$ , the real part of the unsteady aerodynamic contribution to torsion moment due to a unit displacement in  $h$ . Because  $R''_{ah}$  is orders of magnitude smaller than other terms in the torsion moment equation, this error is deemed to have had an insignificant effect on the flutter results.

Regarding potential Error Source 3, it would be nearly impossible to confirm such an error.

### IV. Recalculations in NASA TPs

The recalculations in the three NASA TPs were performed in MATLAB® using the corresponding solution methods originally employed by T&G in their three NACA reports, Refs. [1–3]. As stated earlier, the original solution methods require successive calculations over a range of values of the inverse of reduced frequency,  $1/k$ . For its recalculations, each NASA TP, Refs. [7–9], had its own range and increment of  $1/k$ : Ref. [7] employed a linear distribution of  $1/k$  between 0 and 50, with an increment of 0.0005; Refs. [8,9] employed logarithmic distributions of  $1/k$ , typically between 0.01 and 100, with typically 1000 and 5000 values of  $1/k$ , respectively. These choices resulted in each successive value of  $1/k$  equal to 1.0093 times the previous value (for [8]) and 1.0018 times the previous value (for [9]). References [8] and [9] employed linear interpolation to arrive at their flutter conditions.

### V. Check Calculations in NASA TPs

Check calculations were performed in MATLAB. In the first and third NASA TPs, [7,9], check calculations employed the  $k$ -method; in the second NASA TP, [8], they employed the  $p$ -method. In all cases, including those where T&G’s original results and present recomputed results differed from each other significantly, the check calculations were always in excellent agreement with the recomputed results, giving confidence in the recomputed results. The recomputed results are taken to be correct.

### VI. Comparisons of T&G’s Original Calculations with Recalculations in NASA TPs

This section of the Note contains comparisons of T&G’s original calculations with present recalculations, two each from the three NASA TPs. The manner of distinguishing between the original and recomputed results is through the use of color. Original figures and graphs from NACA 496, 685, and 741 were electronically scanned, and present recalculations were superimposed. The original results in the original NACA reports were depicted as black continuous curves. But in the comparisons in the NASA TPs, the original black curves are overlaid with color bands, and when necessary, a different color for each different parameter or different combinations of parameters within the plot. The recomputed results are symbols in corresponding colors.

There are many comparisons in the three NASA TPs. They cover the extremes in agreement, from poor to excellent. The comparisons that follow were chosen because they illustrate these extremes.

### A. Comparisons from the First NASA TP [7]

Figures 2 and 3 in this Note correspond to Figs. 11 and 14A Part (b) from the first NASA TP [7]. Figure 2 is an example of excellent agreement between original calculations and recalculations; Fig. 3 is an example of poor agreement. Both figures contain flutter boundaries for the 2DOF torsion–flexure case ( $\alpha$ ,  $h$ ) and both have as their ordinate the nondimensional quantity  $F$ , which is proportional to flutter velocity.

In Fig. 2, quantity  $F$  is plotted as a function of the ratio of natural frequencies  $\omega_1/\omega_2$  ( $\omega_h/\omega_\alpha$ ). The parameters specific to this example are

$$\kappa = 0.0025; a = -0.4; b = 1; x_\alpha = 0.2; r_\alpha^2 = 0.25;$$

$$\omega_\alpha = 100; \omega_h/\omega_\alpha \text{ variable}; g_\alpha = g_h = 0$$

As can be seen, the agreement is excellent over the entire extent of the plot.

In Fig. 3, quantity  $F$  is plotted as a function of  $x_\alpha$ , the nondimensional distance from the elastic axis to the center of gravity. Figure 3 was chosen because it illustrates what the present author believes to be a plotting error (Error Source 5) in NACA 496. Figure 3 contains three curves, labeled A, B, and C, corresponding to three different

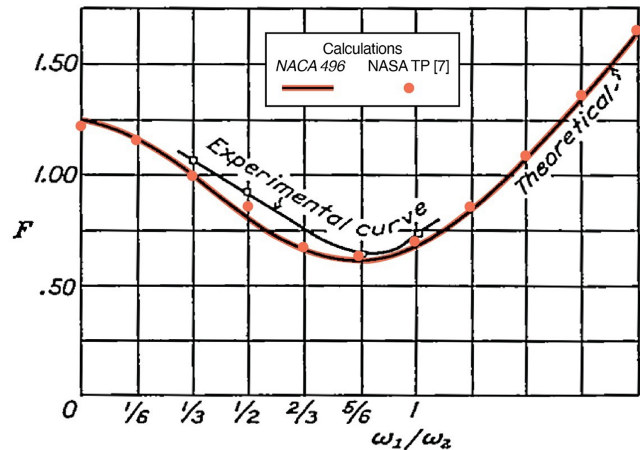


Fig. 2 Figure 11 from first NASA TP [7].

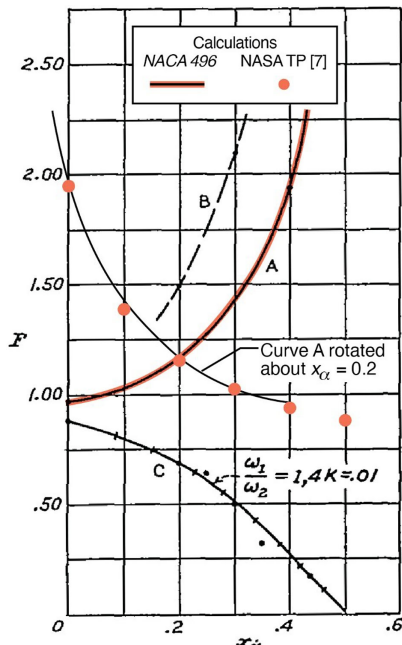


Fig. 3 Figure 14A, Part (b) from first NASA TP [7].

combinations of parameters. This example addresses Curve A only. The parameters specific to Curve A, the focus of this comparison, are

$$\kappa = 0.0025; a = -0.4; b = 1; r_\alpha^2 = 0.25; x_\alpha \text{ variable};$$

$$\omega_\alpha = 100; \omega_h/\omega_\alpha = 0.1667; g_\alpha = g_h = 0$$

The black curve with the orange color band is the original result. The orange-circle symbols are the recomputed results obtained from six executions of Solution Method 1. The original and recomputed results are seen to differ significantly, showing opposite trends with increasing values of  $x_\alpha$ . However, the present author observed the following: the recomputed value of  $F$  at  $x_\alpha = 0$  is very close to the original value of  $F$  at  $x_\alpha = 0.4$ , and vice versa; the recomputed value of  $F$  at  $x_\alpha = 0.1$  is very close to the original value of  $F$  at  $x_\alpha = 0.3$ , and vice versa; and the recomputed value of  $F$  at  $x_\alpha = 0.2$  and the original value of  $F$  at  $x_\alpha = 0.2$  are nearly coincident. This observation led the present author to rotate original Curve A about the vertical axis  $x_\alpha = 0.2$ , shown as the line labeled “Curve A rotated about  $x_\alpha = 0.2$ .”

Rotated Curve A and the orange-circle symbols are in excellent agreement with each other, suggesting that the original Curve A was incorrectly plotted. (Although not presented in Fig. 3, the comparisons for Curves B and C also showed excellent agreements after original Curves B and C were similarly rotated.) In the early 1930s, intricate and multistep engineering calculations, such as those required to produce the results in NACA 496, were performed by hand; results were recorded and transcribed by hand, and then they were plotted by hand. It is not unrealistic to expect that, with the many steps performed by humans, errors occurred. The present author believes that, in the case of Fig. 3, transcription errors occurred (correct values of  $F$  were paired with noncorresponding values of  $x_\alpha$ ), which then led to an incorrect plot.

### B. Comparisons from the Second NASA TP [8]

Figures 4 and 5 in this Note correspond to Graph II-D, Part (b) and Graph II-A, Part (b) from the second NASA TP [8]. Figure 4 is an example of excellent agreement between original calculations and recalculations; Fig. 5 is an example of poor agreement. Both figures contain flutter boundaries for the 2DOF aileron–flexure case ( $\beta$ ,  $h$ ). Both have as their abscissa the ratio of natural frequencies  $\omega_\beta/\omega_h$ , and as their ordinate the nondimensional flutter velocity  $v_f/b\omega_h$ .

Figures 4 and 5 each contain three flutter boundaries, corresponding to different combinations of values of structural damping ( $g_\beta$  and  $g_h$ , Fig. 4) and different values of aileron unbalance ( $x_\beta$ , Fig. 5). All flutter boundaries are hump modes with the same general shape: the hump modes exist at  $\omega_\beta/\omega_h = 0$  and then vanish at higher values of  $\omega_\beta/\omega_h$ .

The parameters specific to Fig. 4 are

$$\kappa = 0.2; b = 6; c = 0; x_\beta = 0.1; r_\beta^2 = 0.05;$$

$$\omega_h = 22.5; \omega_\beta/\omega_h \text{ variable}; g_\beta \text{ variable}; g_h \text{ variable}; \xi = 1$$

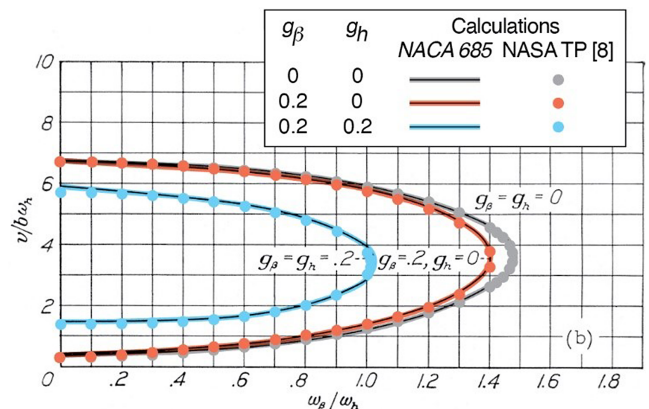


Fig. 4 Graph II-D, Part (b) from second NASA TP [8].

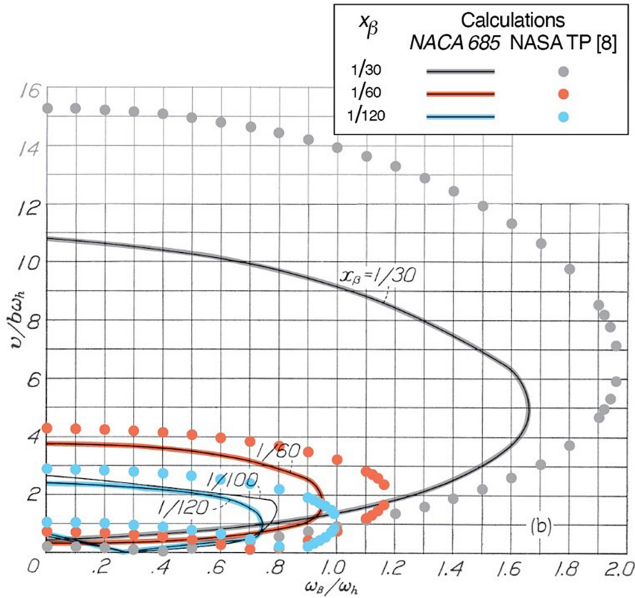


Fig. 5 Graph II-A, Part (b) from second NASA TP [8].

In Fig. 4, the agreement is excellent for each of the three curves over the entire extent of the plot.

The parameters specific to Fig. 5 are

$$\kappa = 0.1; b = 6; c = 0.5; r_\beta^2 = 0.00833; x_\beta \text{ variable}; \\ \omega_h = 22.5; \omega_\beta/\omega_h \text{ variable}; g_\beta = g_h = 0; \xi = 1$$

In Fig. 5, the agreement between the original and recomputed results for each of the three curves is very poor: the magnitude (along the ordinate) and extent (along the abscissa) of each original hump mode is underpredicted. Because of the excellent agreement between original and recomputed results in Fig. 4, it is obvious that T&G could correctly predict hump modes. It is suspected that, in Fig. 5, T&G erred by employing incorrect values of the parameters in their solutions (Error Source 1).

### C. Comparisons from the Third NASA TP [9]

Figures 6 and 7 in this Note correspond to Fig. 9 and the first rendering of Fig. 33, Part (a) from the third NASA TP [9]. Figure 6 is an example of excellent agreement between original calculations and recalculations; Fig. 7 is an example of poor agreement. Both figures contain flutter boundaries for the 3DOF case. Both have as their ordinate the nondimensional flutter velocity  $v_f/b\omega_\alpha$ .

Figure 6 contains a single flutter boundary as a function of  $\xi$ , the partial-span aileron coefficient, which takes on values from 1 (full aileron effectiveness) to 0 (no aileron effectiveness). The abscissa in Fig. 6 is unconventional, beginning at value 1 at the left and ending at value 0 on the right.

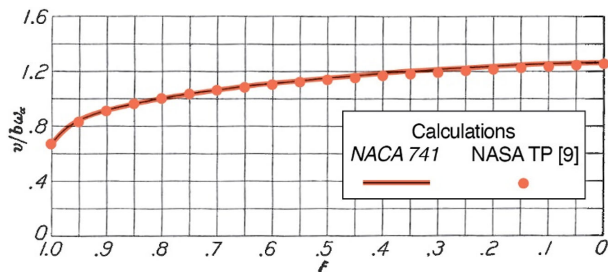


FIGURE 9.—Flutter coefficient  $v/b\omega_\alpha$  against partial-span aileron coefficient  $\xi$ .  $\omega_\beta/\omega_\alpha$ , 0.833;  $r_\alpha^2$ , 1.

Fig. 6 Figure 9 from third NASA TP [9].

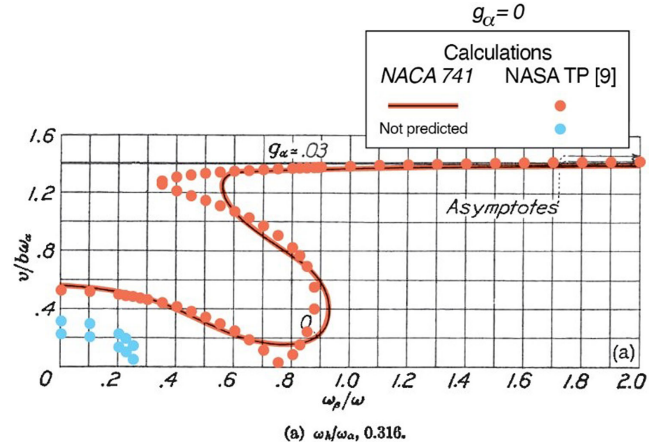


Fig. 7 First rendering of Fig. 33, Part (a) from third NASA TP [9].

The parameters specific to Fig. 6 are

$$\kappa = 0.2; a = -0.2; b = 2.375; c = 0.6; x_\alpha = 0.2; r_\alpha^2 = 1; \\ x_\beta = 0.002; r_\beta^2 = 0.002; \\ \omega_\alpha = 136.136; \omega_\beta/\omega_\alpha = 0.833; \omega_h/\omega_\alpha = 0.607; \\ g_\alpha = g_\beta = g_h = 0; \xi \text{ variable}$$

As can be seen, flutter velocity increases with decreasing values of partial-span aileron coefficient (almost doubling from  $\xi = 1$  to  $\xi = 0$ ), and the agreement between original calculations and recalculations is excellent over the entire extent of the plot.

Figure 7 contains flutter boundaries as a function of the ratio of natural frequencies  $\omega_\beta/\omega_\alpha$ . Although the original figure contains results for two values of structural damping  $g_\alpha$ , the comparison in Fig. 7 is for  $g_\alpha = 0$  only.

The parameters specific to Fig. 7 are

$$\kappa = 0.125; a = -0.2; b = 2.375; c = 0.6; x_\alpha = 0.2; \\ r_\alpha^2 = 0.25; x_\beta = 0.002; r_\beta^2 = 0.002; \\ \omega_\alpha = 136.136; \omega_h/\omega_\alpha = 0.316; \omega_\beta/\omega_\alpha \text{ variable}; \\ g_\alpha = g_\beta = g_h = 0; \xi = 1$$

In Fig. 7, the recomputed results predict an orange S-shaped flutter boundary characterized by a hump mode from about  $\omega_\beta/\omega_\alpha = 0.35$  to about  $\omega_\beta/\omega_\alpha = 0.9$  and a stand-alone blue hump mode from  $\omega_\beta/\omega_\alpha = 0$  to about  $\omega_\beta/\omega_\alpha = 0.25$ . The original results correctly predict an S-shaped flutter boundary, and they agree very well with the recomputed results at the high and low extremes of the S-shape. However, the original results do not correctly capture the details of the “S,” and they completely miss the presence of the blue hump mode. These two shortcomings of the original results are seen to repeat frequently in many of the comparisons in the third NASA TP [9]. The present author suspects that, in this specific case, and in many others revealed in the third NASA TP [9], T&G performed an insufficient number of flutter solutions (at an insufficient number of abscissa quantities) to properly define their flutter boundaries, and, in some instances, to even detect some hump modes that they missed (Error Source 4).

## VII. Conclusions

National Advisory Committee for Aeronautics (NACA) 496 by Theodore Theodorsen, and NACA 685 and 741 by Theodorsen and I.E. Garrick (T&G), were groundbreaking papers at the times of their publications, being the first to offer closed-form solutions to the flutter problem. In an Engineering Note in the Journal of Aircraft in the year 2000, Zeiler identified that NACA 685 and NACA 741

contained errors in some of their plots and that two early aeroelasticity texts reproduced some of those incorrect plots. Zeiler recommended that all numerical examples in these NACA reports be recomputed.

The current Note makes known the existence of three NASA Technical Papers (TPs) that follow Zeiler's recommendation. Each NASA TP recalculates and replots all flutter calculations in a corresponding member of the trilogy of NACA reports and each NASA TP compares its recalculated results with the corresponding original results from the trilogy –

- 1) The first NASA TP relates to NACA 496;
- 2) The second NASA TP relates to NACA 685;
- 3) The third NASA TP, relates to NACA 741.

This Note contains two example comparisons from each NASA TP.

The recomputations in each NASA TP were made using the solution method specific to its corresponding NACA report. The recomputations were checked using modern flutter solution techniques. In all cases, including those where T&G's original results and present recomputed results differed from each other significantly, the check calculations were always in excellent agreement with the recomputed results, giving confidence in the recomputed results.

Zeiler concluded his Note by saying that, if recomputations of the flutter results in T&G's trilogy of NACA reports were undertaken "... it would bring a sense of closure to the groundbreaking work done by Theodore Theodorsen and I. E. Garrick." With humility, it is the sincere hope of the present author that such closure has been achieved.

### Acknowledgments

The author wishes to acknowledge the valuable contributions to this Note made by Mr. G. Lee Pollard, of Rothe Development, Inc. Mr. Pollard is a very talented graphic designer. He assembled the recomputed results generated by the present author, electronically scanned the original figures from the NACA reports, and merged the two to produce the final figures in this Note. Mr. Pollard's skill and enthusiasm made my interactions with him not only very productive, but also very enjoyable.

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