Experimental determination of unsteady aerodynamic coefficients and flutter behavior of a rigid wing

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\begin{abstract}
In this paper, unsteady aerodynamic forces acting on a three-dimensional wing and its aeroelastic behavior are determined experimentally using a novel semi-experimental method. Towards this end, a rigid wing specimen was fabricated and tested in a low speed, subsonic wind tunnel with two motion sensors for plunging and pitching. Time history samples of the wing motion were obtained at a single air speed and processed using the "Aerodynamics is Aeroelasticity Minus Structure" (\textit{AAEMS}) system identification method to generate a reduced-order aerodynamic model in discrete-time, state-space format. Coupling the aerodynamic model with the structural model, obtained from the ground vibration test (\textit{GVT}), results in a reduced-order aeroelastic model that can be analyzed with a variable dynamic pressure. Despite the absence of pressure measurements the model yields a good prediction of aeroelastic behavior, especially for lightly damped modes and for a wide range of dynamic pressures, including the flutter point. It is shown that when the dynamic pressure is at 29.6\% of the critical flutter value the method estimates the flutter speed with less than 2\% error. However, as the reference dynamic pressure is lowered (relative to the flutter dynamic pressure) the flutter prediction becomes less accurate due to the lack of pressure data. The experimental procedure outlined in this paper can be useful when predicting flutter based on data obtained at sub-critical dynamic pressures.

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\end{abstract}

1. Introduction

In the past, serious efforts have been made to utilize wind tunnel and flight test data to predict aeroelastic behavior of aircraft, especially the onset of flutter. Flutter is a well known mechanism by which the air vehicle becomes dynamically unstable through the interaction of fluid and structure. Flutter does not normally occur at low air speeds or dynamic pressures. At increased airspeeds the aircraft may develop unstable oscillations leading to a catastrophic failure. Therefore, it is one of the most critical and dangerous phenomenon to be avoided during the design, analysis, and tests of all aircraft structures. Although there exists analytical models and tools that allow estimating the onset of the dynamic instability, they are often subject to modeling uncertainties and limitations that can produce inaccurate, unreliable results. On the other hand, test data are a direct reflection of the actual aircraft and hence can be used with confidence. Also, it is a common practice in aerospace industry to conduct flight flutter tests before the aircraft enters into service.

There are excellent overview papers that discuss various flutter prediction methods in detail (Lind, 2003a, b; Dimitriadis and Cooper, 2001). They include damping extrapolation, envelop function, Zimmerman–Weissenburger,
discrete-time, autoregressive moving average (ARMA), Flutterometer, and Nissim and Gilyard method. Of these, the damping extrapolation (Kehoe, 1995) is perhaps the most commonly used in aerospace industry due to its simplicity of application. The modal damping values are evaluated at a number of subcritical test points, and curve fitting and extrapolation are performed based on the modal damping values to predict the flutter point. In the envelope function method, the decay shape of impulse response is parameterized without the need to identify the modal damping (Cooper et al., 1993). In the discrete-time ARMA method, the system is identified in discrete-time based on responses to flow turbulence excitation, and Jury stability criterion is applied to introduce stability parameters (Torri and Matsuzaki, 2001). Regardless of the different approaches, these methods introduce stability parameters that are valid only at the specific dynamic pressure under consideration. Therefore, an extrapolation is necessary and the prediction becomes dependent on the method adopted.

To address the aforementioned limitation, the other methods consider a coupled fluid-structure system with a variable dynamic pressure. The Zimmerman–Weissenburger method utilizes the coupled equation of motion, applies the Routh stability criterion using a quadratic stability parameter, and solves for the flutter margin (Zimmerman and Weissenburger, 1964). However, its application is limited to 2 degrees of freedom (the classical bending torsion flutter) with quasi-steady aerodynamics. Later, it was extended to include more degrees of freedom but the method is still limited to the quasi-steady aerodynamics (Prince and Lee, 1993). The Flutterometer method is based on an analytical flutter model rather than aeroelastic systems are identified, an aeroelastic model is constructed and the flutter boundary can be estimated by solving the coupled equations of motion. Once the structural and aerodynamic states are sampled using analysis. The result is a robust aeroelastic stability formulation by which the so called “the worst case flutter boundary” is found by a nonlinear iterative algorithm. Unfortunately, being a robust analysis its flutter margin solution might be too conservative to be realistic. Nissim and Gilyard, 1989 developed a frequency domain system identification scheme in which the aerodynamic and structural properties are extracted by manipulating frequency responses of the airplane at two different dynamic pressures. Once the structural and aerodynamic systems are identified, an aeroelastic model is constructed and the flutter boundary can be estimated by solving the coupled equations of motion. However, a quasi-steady approximation of the unsteady aerodynamics must be made to minimize the number of unknowns and make the operations solvable.

Recently, Kim (2009, 2011) introduced the new system identification scheme, “Aerodynamics is Aeroelasticity Minus Structure (AAEMS)” for coupled fluid-structure systems. The method works directly on time history data of the aeroelastic system measured at a single flight condition, where the aeroelastic response includes not only motion data but also aerodynamic data. Assuming that structural properties are known a priori either from FEM or from a GVT, the method identifies the aerodynamic system in discrete-time, state-space format by ‘subtracting’ the structural sub-states from the aeroelastic states. An aeroelastic model is obtained by coupling the two dynamic models and used to predict the aeroelastic responses, including the flutter point. Using numerical simulations of two CSD/CFD models, it is demonstrated that with only time histories of the airplane motion, one can predict aeroelastic damping and frequency accurately in the vicinity of the reference condition. It was also shown (Kim, 2011) that when samples of surface pressure or other aerodynamic quantities are available in addition to the motion measurements, one can predict the aeroelastic behavior accurately for an entire range of dynamic pressures including the flutter point. The main advantages of this method, apart from its new concept, are that it enables structural engineers to build reduced-order aerodynamic models without heavily relying on CFD, and also minimize the CPU time required for running CSD/CFD simulations. Although it was originally developed for constructing reduced-order aerelastic models based on the numerical simulations with the key advantages that do not exist in the current reduced-order modeling techniques (Epureanu et al., 2000, 2001; Dowell et al., 2004; Shahverdi et al., 2009; Liberge and Hamdouni, 2010), its potential for experimental applications was well recognized early on.

The goal of this work is, based on the aforementioned system identification technique, to establish a new, robust semi-experimental procedure by which one can predict the aeroelastic instability at an increased dynamic pressure. The main purpose is to prove and demonstrate the procedural concept. For this purpose, it is sufficient to work with a simple three-dimensional rigid wing specimen in a low speed, subsonic wind tunnel. For the complete aeroelastic identification, both
the motion and aerodynamic measurements are required. However, it was shown in Kim's numerical simulations that in
the case of simple mode shape utilizing only the motion measurement can result in reasonable predictions of the flutter.
Therefore, for the current demonstration only the motion measurements are used in this test.

In the subsequent sections, the following steps will be described in detail: experimental set up; processing of the data
signals using eigensystem realization algorithm (ERA) (Juang, 1994) and a low pass filter; feeding the filtered signals into
the AAEMS to identify the unsteady aerodynamic system; and finally coupling of the aerodynamic model with the known
structural model to generate a reduced-order aeroelastic model. It will be shown that using the procedure one can
estimate unsteady aerodynamic forces acting on the lifting wing. It will be also shown that through the method the
aeroelastic behavior of the wing is predicted accurately, especially for lightly damped modes, provided that the sensor
signals are taken at an air speed not too far from the tested reference speed.

2. Review of AAEMS

In this section, a brief review of the AAEMS is provided. For details, see Kim (2009, 2011). The objective is to identify the
aeroelastic system for a given Mach number and airspeed such that the identified model can be used for variable dynamic
pressures. Basic assumptions are as follows:

(i) Structure, aerodynamics, and aeroelasticity are dynamically linear.
(ii) The background noises in test data are small or can be subdued.
(iii) A sufficient number of aeroelastic measurements are available.
(iv) The systems are controllable and observable.

Given time histories of aeroelastic responses, i.e. the motion and aerodynamic measurements (e.g., displacements, velocities, and pressures), due to a certain input at zero and a nonzero air speeds, one can perform singular value
decomposition (SVD) of the data to define state vectors \( x, y \) for the structural and aeroelastic systems, respectively. Using a
standard system identification tool, it is possible to identify the two systems in the state-space form:

Structure

\[
\begin{align*}
\dot{x}^n + 1 &= A x^n + B u^n, \\
\dot{w}^n &= C x^n,
\end{align*}
\]

Aeroelasticity

\[
\begin{align*}
\dot{y}^n + 1 &= A_y y^n + B_t u^n, \\
\{ v^n \} &= C_t y^n = \begin{bmatrix} C_v \\ C_w \end{bmatrix} y^n.
\end{align*}
\]

where

\[
\begin{align*}
\dot{w} &= \{ z \} \\
\{ v \} &= \text{measured displacement and velocity (2N),}
\{ v \} &= \text{measured aerodynamic parameter, e.g., pressure.}
\end{align*}
\]

There are three theorems on which the AAEMS is based:

(i) transformations between structural and aeroelastic states,
(ii) aeroelastic states = aerodynamic sub-states + structural sub-states,
(iii) D'Alembert's principle.

With the first theorem one can relate \( x \) and \( y \) (see Fig. 1). The second theorem states that the structural and aerodynamic
sub-states \( Y_s, Y_p \) are additive and complementary such that \( Y = Y_s + Y_p \). Thus, by subtracting \( Y_s \) from \( Y \) one can derive an
equation of motion for the unsteady aerodynamics. Finally, using the third theorem it is possible to find an expression for
the aerodynamic forces acting on the wing surface. The aerodynamic system identified herein can be summarized as

\[
\begin{align*}
\dot{Y}^p + 1 &= A_y Y^n, \\
F^n &= C_y Y^n - A x^n,
\end{align*}
\]

where \( A_y, C_y \) are the aerodynamic system and output sub-matrices, respectively. Coupling the aerodynamic model (4) with
the structural model (1) yields a reduced-order aeroelastic model,

\[
\begin{align*}
\begin{bmatrix} y^{n + 1} \\ w^{n + 1} \end{bmatrix} &= \begin{bmatrix} A_s & B_{s1} \left( \frac{\nu}{V_w} \right) B_{s2} \\ q C_s & A + q \left[ D_{s1} \left( \frac{\nu}{V_w} \right) D_{s2} \right] \end{bmatrix} \begin{bmatrix} y^n \\ w^n \end{bmatrix} + \begin{bmatrix} 0 \\ B \end{bmatrix} u^n.
\end{align*}
\]
with which aeroelastic analyses can be executed for constant Mach-varying density (CMVD) conditions. For example, damping and frequency can be predicted by solving for the eigenvalues of the system matrix of Eq. (5). Fig. 2 illustrates an overall flow chart for the AAEMS process.

3. Experimental set-up

To experimentally apply the AAEMS method, tests were performed in a low speed open-type wind tunnel at Seoul National University. Fig. 3 shows a schematic representation of the test setup. The flutter model has two degree-of-freedom ( dof) with a rigid wing, and is inserted in a test section which has dimensions of 0.4 m height \((H)\times 0.45\) m width \((W)\times 1.3\) m length \((L)\). One degree of freedom is plunging motion along the \(y\)-axis and the other is the pitching motion with respect to the \(z\)-axis. The airfoil and its shaft are made of steel. The wing has a diamond shape cross section with 0.10 m chord, 0.15 m span, and 0.012 m maximum thickness. A cylindrical shaft with 0.011 m diameter and 0.57 m length is located at the center of mass of the wing and works as the pitch axis. The shaft is mounted on a moving plate at both ends by bearing to ensure the pitching motion. To provide the plunging motion, the moving plate is connected to the support plate attached on the outside of test section by bending springs. The bending springs for the plunge motion are 0.19 m long, 0.039 m wide, and 0.001 m thick, and made of spring steel. For the pitch motion a bending spring is also used instead of a usual torsion spring to enhance linearity. The pitch bending spring is made of steel and is 0.032 m long, 0.002 m wide and 0.0006 m thick. One end is fixed at the axis and the opposite end is fixed at the moving plate. To produce an impulse input forces, a steel bar has been used to strike the wing.

Three sensors were placed to detect the pitching and plunging motion, and the excitation force. Pressure sensors were not installed in this test. The plunging motion was measured by an integrated electronic piezo electric type (IEPE) accelerometer adhered to the upper moving plate. For the pitching motion, a rotary variable differential transformer (RVDT) was mounted at the end of the shaft so that the angular displacement can be detected. The excitation force is
measured by an IEPE type dynamic force transducer, which is mounted at the end of the excitation bar. Output signals from these sensors are amplified and sent to an analog to digital converter (A/D converter), and then transferred to a desktop computer for data processing.

4. Data reduction

To execute the system identification, time history data of wing displacements and velocities are needed. However, in the present test only the plunge acceleration and the pitch displacement are available. Therefore, it is necessary to integrate the acceleration twice and differentiate the displacement once. Fig. 4 illustrates a flow chart for the data reduction where sensor output signals are processed using different schemes at various stages.

First, using the A/D converter analog signals from the sensors are discretized at 500 Hz ($\Delta t = 0.002$ s). Then, the ERA is used to smooth out the raw data. During the integration of the plunge acceleration the ERA is used again to remove low frequency noises that could introduce unnecessary drifting in the velocity and displacement responses. But such a treatment is not essential during the differentiation of the pitch signal. A low pass filter (LPF) is also employed for the displacement and velocity data of the two motions to remove some unnecessary structural modes (see Section 5). Finally, the ERA is applied to the resultant displacement and velocity data at zero and non-zero airspeeds to produce state-space matrices for the structural and aeroelastic systems, respectively. The AAEMS then takes these system models and produces an aerodynamic model.

It is important to know that the purpose of using the AAEMS and the data processing is not for the sake of the system identification itself. Rather, these tools are used as means to predict the aeroelastic behavior and flutter. On the other hand, the true system identification is all together more difficult and as such it may need a procedure more sophisticated and robust than the one described in the present section.
5. Results and discussion

To demonstrate the applicability of the AAEMS and validate the procedure outlined, two sets of experiments were performed. The first test was done to obtain the actual flutter speed and frequency. The flutter speed was found to be 25 m/s and the corresponding frequency was 47.71 rad/s. The second set of tests was done to measure impulse responses of the wing with and without the air flow. The impulse responses herein refer to time responses of the plunging acceleration and pitching displacement subject to an impulse input applied to the wing. Without the flow ($V=0$) the system is considered to be a purely structural system, whereas with the flow ($V=V_{ref}$) it is an aeroelastic system. To see the effects of reference speed on the flutter prediction, four flow speeds were chosen at 0 m/s, 9.6 m/s, 13.6 m/s, 19.6 m/s.

Figs. 5 and 6 show, respectively, frequency responses of the plunge acceleration and the pitch displacement at $V=0$ m/s and 19.6 m/s. In both plots the plunging acceleration has three apparent peaks while the pitching displacement has a single apparent peak. At $V=0$ m/s, the plunge motion has peaks at 47 rad/s (plunging mode), 102.2 rad/s (rolling mode), and 540.6 rad/s (noise). The rolling mode arises because there exists a second mode of the plunging bending spring along the $x$-axis and hitting at the exact center of mass is difficult. The single apparent peak in the pitching frequency response is the pitching mode (56.58 rad/s at $V=0$).

The raw and filtered signals at $V=19.6$ m/s are shown in Fig. 7. Not surprisingly, these signals show high and low frequency noises. As explained in the previous section, the ERA is used to filter out noises which arise from external sources and during the integration. The advantage of using this algorithm is that based on the SVD it extracts the most dominant modes out of the raw signal, so the reproduced impulse responses from the identified models can exclude noises without loss of important modes. The ERA will also fit the original data into a rational form with poles and zeros and this strategy is consistent with the AAEMS that comes in at a later stage so that both processes will then be based on the same type of data processing. Since there were only two motion sensors available only two structural modes could be identified. It was necessary to sense the plunge and pitch because they are the major modes responsible for the aeroelastic instability. Thus, the third dominant structural mode, the rolling, had to be removed from the signals before the system identification was executed. Otherwise, the consequent aerodynamic model would contain aerodynamic modes associated with the roll mode, since roughly the AAEMS subtracts the plunge and pitch modes from the plunge, pitch, roll, and aerodynamic modes. The roll mode was removed by a LPF with a cut-off frequency of 90 rad/s. Although both ERA and LPF were adopted there is no visible difference between the raw and filtered signals as shown in the figure.
Fig. 5. Frequency responses at $V_{ref} = 0$ m/s: (a) plunge acceleration, (b) pitch displacement.

Fig. 6. Frequency responses at $V_{ref} = 19.6$ m/s: (a) plunge acceleration, (b) pitch displacement.

Fig. 7. Raw versus filtered signals at $V_{ref} = 19.6$ m/s: (a) plunge acceleration, (b) pitch displacement.
Using the two sets of filtered signals at $V=0\,\text{m/s}$ and $V=V_{\text{ref}}$, the structural and aeroelastic reduced-order models (ROMs) for the AAEMS are identified by the ERA. During the process, the ROM size should be determined and that is related to the modes of systems. Since only the two structural modes could be identified, the structural ROM size should be 4. Similarly the aeroelastic ROM should include two structural modes and aerodynamic modes, so the aeroelastic ROM size should be 4 (structure) plus $\alpha$ (aerodynamics). In our case, sizes of the aeroelastic ROMs ($V_{\text{ref}}=9.6\,\text{m/s}$, $13.6\,\text{m/s}$, and $19.6\,\text{m/s}$) are respectively 6, 8, and 9. Details of how the aeroelastic ROM sizes were determined will be discussed at the end of the section. Subsequently, after applying the AAEMS to the structural and the aeroelastic systems, the aerodynamic ROM described by Eq. (4) was obtained and an aeroelastic ROM for variable dynamic pressure was generated as in Eq. (5).

Fig. 8(a) and (b) show the eigenvalues of the structural and the aeroelastic systems, and Fig. 8(c) displays eigenvalues of the aerodynamic system produced by the AAEMS. It is interesting to see that the aerodynamic eigenvalues are approximately the aeroelastic eigenvalues minus the structural eigenvalues. This implies a very important aspect of the aeroelastic system. That is, the aerodynamic and structural systems are only weakly coupled. If they were completely decoupled, the aerodynamic poles would be exactly the aeroelastic poles minus the structural poles. If they were strongly coupled, the aerodynamic poles would be very different from the aeroelastic poles minus the structure poles.

Using the resultant aeroelastic models, flutter speed and frequency were predicted and the results are summarized in Table 1. In all of the calculations, a constant air density was used assuming incompressible flow conditions. Although the test cases ($V_{\text{ref}}=19.6\,\text{m/s}$, $13.6\,\text{m/s}$, $9.6\,\text{m/s}$) have respectively 60.5%, 29.6%, 14.7% dynamic pressures of $q_{\text{flutter}}$, the critical dynamic pressure at flutter, the flutter predictions are reasonable to excellent. In particular, at $V_{\text{ref}}=13.6\,\text{m/s}$ it was possible to predict the flutter speed with less than 2% error. Additionally, it can be noticed that as $V_{\text{ref}}$ decreases the prediction becomes less accurate. This trend was already observed by Kim and a potential remedy was suggested in numerical applications of the AAEMS (Kim, 2009, 2011). That is, sampling and adding wing surface pressures in the data set improves the results.

![Fig. 8.](image-url)
For comparison of flutter prediction capability, Zimmerman and Weissenburger’s method was applied to the test data at three different reference speeds ($V_{\text{ref}} = 19.6 \text{ m/s}$, $13.6 \text{ m/s}$, $9.6 \text{ m/s}$), and yielded a predicted flutter speed of $20.89 \text{ m/s}$, with 16.4% error. One source of the inaccuracy is the quadratic variation which is established based on zero structural damping assumption. Contrary to this assumption, Fig. 9 shows a considerable structural damping in the pitch mode. Moreover, the Zimmerman’s method uses a quasi-steady aerodynamic assumption which could also be the cause for this inaccuracy.

Fig. 9 shows the growth rate vs. dynamic pressure plot based on the aeroelastic model obtained at $V_{\text{ref}} = 19.6 \text{ m/s}$ ($q_{\text{ref}} = 230.2 \text{ N/m}^2$). For comparison also shown in the figure are growth rates and frequencies obtained from the test data at $V = 0, 9.6, 13.6, 19.6,$ and $25 \text{ m/s}$ ($q = 0, 55.2, 110.8, 230.2, 374.5 \text{ N/m}^2$). It is seen that the damping and frequency of the lightly damped plunge mode are well captured at all speeds by the current method. However, for the pitch mode, which is the more damped of the two, the damping coefficient is not predicted as well except at low reference speeds. Its frequency, however, is still quite well captured. Interestingly, the plunge mode becomes unstable at the flutter point and this unusual phenomenon can be attributed to the high structural damping in the pitch mode. To gain confidence, the flutter mode was examined by a numerical simulation with a 3D vortex lattice model and it showed the same trend as the AAEMS prediction. With assumed low structural damping in the pitch mode a pitching flutter with merging pitch and plunge frequencies would have occurred as opposed to the plunging flutter seen in the present test.

Figs. 10 and 11 show aerodynamic forces at the three reference speeds. They are not the physical aerodynamics forces as we know, e.g., lift and moment, but are aerodynamic forces scaled by structural masses for the two degrees of freedom. As can be seen from the figures, the aerodynamic forces are indeed smooth functions of the frequency. They correspond well in magnitude with each other for a wide range of frequencies, but the phases are similar only within a limited frequency range. It can be expected that the aerodynamic system generated at a particular reference speed will accurately reproduce the aerodynamic forces in the neighborhood of the structural resonance frequencies at that speed and hence the resulting aeroelastic system should be also accurate in the vicinity of the reference speed. Thus, the aerodynamic system generated at $V_{\text{ref}} = 19.6 \text{ m/s}$ will most accurately capture the aerodynamics near the flutter point, $V = 25 \text{ m/s}$, while the aerodynamic system generated at $V_{\text{ref}} = 9.6 \text{ m/s}$ will be least accurate. It can be also observed that the number of aerodynamic states increases with the airspeed. This is because the aerodynamics becomes more dominant at higher dynamic pressures making the aerodynamic identification more complete. Again, to improve the accuracy of the aerodynamic models and make them valid for the entire frequency range regardless of the reference speed, it is recommended to include aerodynamic pressure samples in the data set (Kim, 2011).

Finally, a discussion on the effect of selected singular modes and their physical meaning is in order. During the ERA process we need to decide which singular modes should be included for best approximation. Ideally, the more singular modes are included the more accurate the model should become. However, the sensors’ data includes significant amount

### Table 1

<table>
<thead>
<tr>
<th>Experiment</th>
<th>AAEMS prediction</th>
<th>Zimmerman's prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured flutter speed (m/s)</td>
<td>25</td>
<td>Predicted flutter speed (m/s) 25.2 24.6 19.6</td>
</tr>
<tr>
<td>Measured flutter frequency (rad/s)</td>
<td>47.71</td>
<td>Predicted flutter frequency (rad/s) 49.36 47.02 57.06</td>
</tr>
</tbody>
</table>

Fig. 9. Growth rate vs. dynamic pressure plot based on aeroelastic model at $q_{\text{ref}} = 230.2 \text{ N/m}^2$ ($V_{\text{ref}} = 19.6 \text{ m/s}$).
Fig. 10. Aerodynamic force for plunge mode: (a) magnitude (b) phase.

Fig. 11. Aerodynamic force for pitch mode: (a) magnitude (b) phase.

Fig. 12. Singular value plot of ERA: aeroelastic system at 9.6 m/s.
of noise, and the resultant aeroelastic models must work not only at $V_{\text{ref}}$ but also for a wide range of flow speeds. Hence, a mere increase in the number of singular modes may not necessarily result in a higher accuracy in the model. It would seem necessary to select only those singular modes that are not greatly affected by noise and yet pertain to the aerodynamics associated with the retained structural modes. One way to strive for a good selection of the modes would be to rely on the singular values vs. mode index plot. Fig. 12 is a singular value plot of the aeroelastic system at $V_{\text{ref}}=9.6$ m/s. From the figure, it is clear that the singular modes can be split into the dominant part (modes 1 through 6) and the negligible part (modes 7 and the rest). Excluding the dominant modes would mean missing important information, whereas including the negligible modes implies adding unnecessary and distorted information. Thus, one is led to pick the first six modes and six becomes the optimal mode number. It can be said that four out of the six modes are closely associated with the structure and the remaining two modes would account for the unsteady aerodynamics. In unsteady aerodynamics the latter are sometimes called aerodynamic lag states. Table 2 shows flutter speed and frequency vs. the number of singular modes chosen at different reference speeds. It is seen that the best result is always obtained when an optimal number of modes are judiciously selected. Otherwise, the results are rather sensitive to the number of modes selected, but at the high speed (19.6 m/s) the sensitivity is low.

6. Conclusions

In this paper, a new semi-experimental procedure is presented that allows to estimate unsteady aerodynamic loads and predict the aeroelastic instability for a variable range of dynamic pressures. The method is applied to time histories of a three-dimensional rigid wing in a low speed, subsonic wind tunnel. Based on the AAEMS system identification technique, plunge and pitch sensor signals at zero and a nonzero reference speeds are processed, and an aerodynamic system is generated by subtracting the structural sub-states from the aeroelastic states. To fit into the overall system identification scheme, the raw time samples are filtered using the ERA. A low pass filter (LPF) has also been adopted to eliminate unnecessary modes in the signals. When the identified aerodynamic model is coupled with the known structural model, a reduced-order aeroelastic model that is valid for variable dynamic pressure is generated.

Despite the absence of aerodynamic pressure measurements, the resulting aeroelastic model predicts the aeroelastic behavior at an increased dynamic pressure with a good accuracy, provided that the reference dynamic pressure is not too far from the point of interest. Therefore, the method can be efficiently used to predict the onset of flutter. Specific conclusions are follows:

(i) for a test speed of 13.6 m/s whose dynamic pressure is 29.6% of the flutter point (25 m/s), the proposed method estimates the flutter speed with less than 2% error;
(ii) as the reference speed is lowered, the prediction becomes less accurate yielding 21.6% error in the flutter speed for the reference speeds of 9.6 m/s (14.7% of the flutter point);
(iii) lightly damped aeroelastic modes are better predicted than heavily damped modes;
(iv) aerodynamic poles are approximately the aeroelastic poles minus structural poles;
(v) best results are obtained by selecting the dominant singular modes following the singular value plot.

To improve the accuracy of the flutter prediction at low reference speeds, it will be necessary to install pressure gauges on the wing surface and add the aerodynamic measurements in the data set. It might be also necessary to increase the number of motion sensors to capture some of the high frequency modes such as the rolling. Finally, a robust and automated scheme that selects optimum singular value modes must be developed and implemented.
References


