Gain scheduling in receptance-based control of aeroelastic systems

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Abstract
This research considers the development of gain-scheduling approaches in receptance-based control of aeroservoelastic systems. The Receptance-Method is extended so that the control gains are variable with respect to the freestream speed. This enables the system's poles to be placed at a set of reference speeds and not just a single speed. In the standard Receptance Method, input-output transfer function data can only be collected at speeds well below the open-loop flutter speed. This means that the flutter speed is often not pushed as high as is possible, within the physical constraints of the controller. This problem is circumvented through the development of an iteration technique, whereby the control gains are computed as a modification to an existing controller, which is active during collection of the receptances. The method is tested numerically on a reference pitch-plunge aeroelastic model. It is shown that the flutter speed can be successfully increased with such an approach and that the technique has scope for applications in large-scale aircraft.

1 Introduction

With the advent of composite materials with large specific strengths and the continued development of highly precise manufacturing processes, aircraft are becoming increasingly lightweight and flexible. Although increasing fuel and aerodynamic efficiency, these next generation aircraft are more susceptible to detrimental aeroelastic phenomena, such as divergence, control reversal, and flutter. Flutter, in particular, presents a significant problem in modern aircraft and, if not mitigated during the design phase, can lead to fatigue, damage or even structural failure.

In recent years, active flutter suppression (AFS) has been proposed as a solution to the above-mentioned problem. AFS systems use one or more actuators, usually in the form of control surfaces, to modify the dynamics of the aerostructure such that the speed at which flutter arises is pushed higher. This enables aircraft to fly at higher speeds, without the need for weight-inducing structural modifications. Although this technique has significant benefits over traditional, passive solutions, conventional AFS methods require accurate modelling of the structure and aerodynamic during the design phase. This is particular difficult in complex aeroelastic systems and usually one must be prepared to accept some degree of uncertainty in the new, modified flutter speed.

In recent years, receptance-based control approaches have been used in aeroservoelastic systems [1, 2, 3]. These techniques use input-output transfer function data, measured experimentally be means of modal testing, to perform eigenstructure assignment. This avoids the problems associated with numerical modelling and produces a controller that is designed without the need to estimate structural or aerodynamic parameters. One particular technique that is widely used is known as the Receptance Method [4, 5, 6] and has been applied to numerous experimental models. Despite the promising results, however, it is yet to be extended to large, full-scale aircraft. One of the limiting factors is the use of fixed gains in the feedback controller.

The Receptance Method, as it is defined today, considers only linear time-invariant systems. That is, linear systems with fixed mass, stiffness and damping parameters. Aeroelastic systems, however, are parameter dependent; usually the varying parameter is taken to be the freestream speed or dynamic pressure. Therefore, if the technique is to be applied commercially, this limitation must be addressed.

This work considers the extension of the Receptance Method to consider gain scheduling. This allows the controller to vary according to the freestream speed and thus the performance can be improved significantly. By extending the Receptance Method to parameter varying systems, control gains are calculated at a set of reference speeds and an interpolation method is used. Conventionally, the Receptance Method can only be applied at speeds where the open-loop system is stable. However, in this work, this limitation is mitigated through the development of a controller iteration method, which allows the input-output transfer function vectors to be measured at speeds well beyond the original flutter speed.

The outline of this paper is as follows. Firstly, the fundamental theory of the gain scheduling approach is discussed. Next, the technique is tested numerically on a reference aeroseroelastic model that is widely used in the literature. Finally, a discussion of the results is given and areas of future work are identified.

2 Methodology

This section outlines the theory of the proposed technique. First, the gain-scheduling approach is introduced and a brief review of the Receptance Method is given. Following this, a control iteration method is developed, which allows closed-loop receptance data to be used to find the necessary gains for eigenvalue assignment. Next, an optimisation-based approach is detailed and the process of optimum eigenvalue assignment is outlined. Finally, a gain interpolation method, which enables a smooth transition of the control gains with respect to the freestream speed, is discussed.

2.1 Gain-Scheduling

Consider a single-input, n-degree-of-freedom linear aeroservoelastic system governed by the input-output equation

$$\mathbf{x}(s) = \mathbf{r}(s, v)u(s) \tag{1}$$

where $\mathbf{x}(s) \in \mathbb{C}^n$ is the output vector, $\mathbf{r}(s, v) \in \mathbb{C}^n$ is the transfer function vector, and $u(s) \in \mathbb{C}$ is the input. In the standard Receptance Method [4], the input is selected as

$$u(s) = \left(s\mathbf{f}^T + \mathbf{g}^T\right)\mathbf{x}(s) \tag{2}$$

where $\mathbf{f}, \mathbf{g} \in \mathbb{R}^n$ are vectors of control gains. However, in this study, the input equation is modified to

$$u(s, v) = \left(s\mathbf{f}(v)^T + \mathbf{g}(v)^T\right)\mathbf{x}(s) \tag{3}$$

That is, the input is scheduled according to some variable $v \in \mathbb{R}$. In this work, v is taken as the freestream speed. This is a natural choice for aeroservoelastic systems where both viscosity and compressibility effects may be ignored. Substituting Eq. 3 into Eq. 1 gives that

$$\mathbf{x}(s) = \mathbf{r}(s, v)\left(s\mathbf{f}(v)^T + \mathbf{g}(v)^T\right)\mathbf{x}(s) \tag{4}$$

The aim is to now design a controller, and hence determine the required control gains, across the domain of v.

Suppose that a set of reference speeds is chosen and is denoted by $\{v_1, v_2, \ldots, v_p\}$. Further suppose that at each speed v_j the set of closed-loop poles is $\boldsymbol{\mu}_j = \{\mu_{j_1}, \mu_{j_2}, \ldots, \mu_{j_{2n}}\}$, which is closed under conjugation. The eigenvalue problem associated with Eq. 4 becomes

$$\mathbf{w}_{j_i} = \mathbf{r}(\mu_{j_i}, v_j)\left(\mu_{j_i}\mathbf{f}(v_j)^T + \mathbf{g}(v_j)^T\right)\mathbf{w}_{j_i}, \quad i = 1, 2, \ldots, 2n, \quad j = 1, 2, \ldots, p \tag{5}$$

Since the eigenvectors may be scaled arbitrarily, $\mathbf{w}_{j_i}$ is selected such that

$$\left(\mu_{j_i}\mathbf{f}(v_j)^T + \mathbf{g}(v_j)^T\right)\mathbf{w}_{j_i} = 1, \quad i = 1, 2, \ldots, 2n, \quad j = 1, 2, \ldots, p \tag{6}$$

Therefore, by substituting Eq. 6 into Eq. 5,

$$\mathbf{w}_{j_i} = \mathbf{r}(\mu_{j_i}, v_j), \quad i = 1, 2, \ldots, 2n, \quad j = 1, 2, \ldots, p \tag{7}$$

and so

$$\mathbf{r}(\mu_{j_i}, v_j)^T \left(\mu_{j_i}\mathbf{f}(v_j) + \mathbf{g}(v_j)\right) = 1, \quad i = 1, 2, \ldots, 2n, \quad j = 1, 2, \ldots, p \tag{8}$$

This form allows the gains to be solved as follows. Let

$$\mathbf{P}(v_j) = \begin{pmatrix} \mu_{j1}\mathbf{r}(\mu_{j1}, v_j)^T & \mathbf{r}(\mu_{j1}, v_j)^T \\ \mu_{j2}\mathbf{r}(\mu_{j2}, v_j)^T & \mathbf{r}(\mu_{j2}, v_j)^T \\ \vdots & \vdots \\ \mu_{j2n}\mathbf{r}(\mu_{j2n}, v_j)^T & \mathbf{r}(\mu_{j2n}, v_j)^T \end{pmatrix} \tag{9}$$

and

$$\mathbf{e} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \tag{10}$$

The control gains necessary to assign the desired set of closed-loop poles at each speed v_j is given by

$$\begin{pmatrix} \mathbf{f}(v_j) \\ \mathbf{g}(v_j) \end{pmatrix} = \mathbf{P}(v_j)^{-1}\mathbf{e} \tag{11}$$

Eq. 11 is valid if, and only if, the set of closed-loop poles and the set of open-loop poles are distinct. In practice, some poles may be unmodified from the open-loop and thus an alternative approach is required. Further details on how to deal with this situation are provided in [6].

2.2 Controller Iteration

The procedure given above calculates the control gains using the open-loop input-output transfer function matrix at each freestream speed. Since the transfer function matrix can only be measured experimentally when the system is stable, one cannot apply the method at speeds close to or above the flutter speed. This significantly restricts the usefulness of the technique since a flutter suppression controller can only be designed at speeds below the original, open-loop flutter speed. Because of this, it is often the case that the designed controller is far from optimum and may not push the flutter speed as high as possible.

Here, an alternative strategy is considered that allows closed-loop input-output transfer function data to be used. This is done by updating the controller using an iterative approach so that speeds above the original open-loop flutter speed may be considered.

Suppose instead that the input in Eq. 3 is modified to

$$u(s, v_j) = u(s, v_{j-1}) + \Delta u(s, v_j) = \left(s\mathbf{f}(v_{j-1})^T + \mathbf{g}(v_{j-1})^T\right)\mathbf{x}(s) + \left(s\Delta\mathbf{f}(v_j)^T + \Delta\mathbf{g}(v_j)^T\right)\mathbf{x}(s) \tag{12}$$

That is, the input at the speed v_j is comprised of the controller corresponding to the speed v_{j-1} and a subsequent modification to that controller. Substituting Eq. 12 into Eq. 1 gives that

$$\mathbf{x}(s) = \mathbf{r}(s, v_j)\left(s\mathbf{f}(v_{j-1})^T + \mathbf{g}(v_{j-1})^T\right)\mathbf{x}(s) + \mathbf{r}(s, v_j)\left(s\Delta\mathbf{f}(v_j)^T + \Delta\mathbf{g}(v_j)^T\right)\mathbf{x}(s) \tag{13}$$

or equivalently

$$\left(\mathbf{I} - \mathbf{r}(s, v_j)\left(s\mathbf{f}(v_{j-1})^T + \mathbf{g}(v_{j-1})^T\right)\right)\mathbf{x}(s) = \mathbf{r}(s, v_j)\left(s\Delta\mathbf{f}(v_j)^T + \Delta\mathbf{g}(v_j)^T\right)\mathbf{x}(s) \tag{14}$$

This may be written more compactly in the form

$$\mathbf{x}(s) = \hat{\mathbf{r}}(s, v_j)\left(s\Delta\mathbf{f}(v_j)^T + \Delta\mathbf{g}(v_j)^T\right)\mathbf{x}(s) \tag{15}$$

where

$$\hat{\mathbf{r}}(s, v_j) = \left(\mathbf{I} - \mathbf{r}(s, v_j)\left(s\mathbf{f}(v_{j-1})^T + \mathbf{g}(v_{j-1})^T\right)\right)^{-1}\mathbf{r}(s, v_j) \tag{16}$$

The term $\hat{\mathbf{r}}(s, v_j)$ is the equivalent closed-loop transfer function vector and, analogous to Eq. 1, gives the input-output relationship but now with the controller corresponding to v_{j-1} active at the speed v_j. This is advantageous as the flutter speed can be gradually increased; the constraint of designing a controller below the open-loop flutter speed is removed.

The process given above calculates the control gains at v_j as a modification to the controller v_{j-1}. It is straightforward, however, to convert these control gains back to a form that represents a modification to the open-loop transfer function vector at v_j, despite this quantity not being measured. Using Eq. 12, it is easily verified that

$$\mathbf{f}(v_j) = \mathbf{f}(v_{j-1}) + \Delta\mathbf{f}(v_j) \tag{17}$$

$$\mathbf{g}(v_j) = \mathbf{g}(v_{j-1}) + \Delta\mathbf{g}(v_j) \tag{18}$$

and thus

$$\mathbf{f}(v_j) = \mathbf{f}(v_1) + \sum_{i=2}^{j}\Delta\mathbf{f}(v_i) \tag{19}$$

$$\mathbf{g}(v_j) = \mathbf{g}(v_1) + \sum_{i=2}^{j}\Delta\mathbf{g}(v_i) \tag{20}$$

The iterative-based control technique is summarised as follows:

1. Collect the open-loop input-output transfer function vector experimentally at the initial speed v_1.
2. At the speed v_1, choose the desired eigenvalue assignment and solve Eq. 11
3. With the controller from (2) active, collect the new transfer function vector $\hat{\mathbf{r}}(s, v_2)$.
4. At the speed v_2, perform the desired eigenvalue assignment and calculate the modified control gains.
5. Repeat (3)-(4) at each speed in the set $\{v_1, v_2, \ldots, v_p\}$.
6. Once all modification control gains have been computed, use Eqs. 19 and 20 to determine the control gains with respect to the open-loop system.

2.3 Optimum Eigenvalue Assignment

The technique developed above allows the poles to be assigned using closed-loop equivalent input-output transfer function data. It does not, however, consider *where* to best place the poles at each freestream speed or the effect each controller has on the flutter speed.

A significant drawback of receptance-based techniques is that, since only experimental data is used, the effect of a controller on the flutter speed cannot be explicitly predicted. Indeed, it is only the location of the poles at the chosen set of reference speeds that can be determined. An, at first, obvious strategy is to place the poles so that the damping is increased as much as possible. In other words, to maximally increase the margin of stability. This approach, however, does not necessarily guarantee that the flutter speed is pushed higher. As shown by Mokrani [3], the flutter speed is actually pushed higher by either: (i) increasing damping in *particular* modes, (ii) increasing the frequency separation between modes, or (iii) a combination of (i) and (ii). In this work, the final strategy of separating both the frequencies and increasing the damping is used.

Let each pole μ_{j_i} be decomposed as

$$\mu_{j_i} = -\zeta_{j_i}\omega_{j_i}(+/-)\omega_{j_i}\sqrt{1-\zeta_{j_i}^2}\mathrm{i} \tag{21}$$

where ζ_{j_i} and ω_{j_i} are the damping ratio and natural frequency of each pole, respectively. At each speed v_j an objective function is defined as

$$\rho_j = -\min\left(\zeta_j | \zeta_j \in \{\zeta_{j_i}\}_{i=1}^n\right) + \alpha \max\left(\frac{1}{(\omega_{j_i}-\omega_{j_k})^2} | \omega_{j_{i,k}} \in \{\omega_{j_{i,k}}\}_{i,k=1,i\neq k}^n\right) \tag{22}$$

where α is a constant that weights the frequency separation penalty to the minimum damping penalty.

Let a set of gain constraints be written as

$$\sqrt{\mathbf{f}^T\Lambda_f\mathbf{f}} + \sqrt{\mathbf{g}^T\Lambda_g\mathbf{g}} \leq c \tag{23}$$

where $\Lambda_f, \Lambda_g \in \mathbb{R}^{n\times n}$ are diagonal matrices with entries that weight the control gains associated with $\mathbf{f}$ and $\mathbf{g}$. The optimisation problem is:

Optimisation: Minimise the objective function in Eq. 22 by placing the system's poles subject to the constraints given in Eq. 23.

In general, there is no guarantee that the objective function is convex. Therefore, traditional gradient-based optimisation methods may become stuck on local minima, which lie far from the optimum solution. To avoid this problem, a global optimisation approach is used in this work. The specific algorithm used is the Differential Evolution method presented by Storn and Price [7]. It has been shown in the literature that this optimisation is appropriate for use in receptance-based methods [8, 9].

2.4 Gain Interpolation

Thus far, the control gains have been calculated at a discrete number of freestream speeds. Therefore, the behaviour of the controller is presently undefined for other speeds. To remedy this, a gain interpolation method is developed.

2.4.1 Spline Interpolation

As before, let the control gains at each speed v_j be denoted by $\mathbf{f}(v_j)$ and $\mathbf{g}(v_j)$. Between each pair v_j and v_{j+1} the aim is to find a vector of polynomials $\mathbf{q}(v)$ such that $\mathbf{q}(v_j) = [\mathbf{f}(v_j)^T\mathbf{g}(v_j)^T]^T$ and $\mathbf{q}(v_{j+1}) = [\mathbf{f}(v_{j+1})^T\mathbf{g}(v_{j+1})^T]^T$. This can be achieved by using a third order spline interpolation between this points and is the method used in this work. Such an approach minimises the 'bending' of the curve whilst also enforcing that the curve passes through the calculated gains found using the iterative method.

2.4.2 Controller Transition Zone

The spline interpolation method produces a smooth variation in the control gains between the fixed speed measurements. It does not, however, consider the behaviour below the lowest speed v_1. One strategy is to extrapolate the control gains linearly so that the controller corresponding to v_1 is used for speeds at or below v_1. Although conceptually straightforward and easy to implement, this approach suffers from several drawbacks. One such drawback is that, at speeds well below v_1 the poles will not be assigned to the locations required in v_1 and thus it is possible that the controller may push the system unstable. This is especially problematic in aeroelastic systems where there is a transition between the inertia and aerodynamic effects on the dynamics of the control surfaces.

To counteract the above-mentioned problems, a so-called 'control transition zone' is introduced. At speeds below v_1, the gains are linearly interpolated from a zero vector at 0 m/s to the gains calculated at v_1. Above the final speed v_p, the control gains are fixed at the final values and remain static up to the closed-loop flutter speed, where the system then becomes unstable.

3 Case Study

In this section, the gain scheduling method is applied to a numerical aeroservoelastic model. First, the model is described and key results from the open-loop system are presented. Following this, the iterative based control approach is used and the effect of varying the frequency separation metric is discussed. Finally, the gain interpolation method is applied and the final controller is tested.

3.1 Numerical Model

The model used in this work is that of Platanitis and Strganac [10]. It is a standard reference model, widely used in the research community, and is a typical pitch-plunge system, as shown in Fig. 1. The system is restrained by two springs, one placed in the pitch degree-of-freedom and one placed in the plunge degree-of-freedom. The aerofoil is equipped with two control surfaces; one at the leading-edge and one at the trailing-edge. In this work, however, only the trailing-edge control surface is used and the system is thus treated as single input. The aerodynamics are approximated by a quasi-steady model and have been verified experimentally, as detailed in the original paper [10].

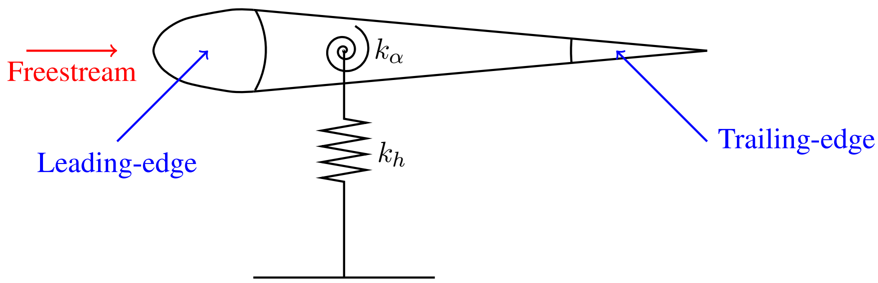


Figure 1: Platanitis and Strganac 2-DoF aerofoil.

Figure 2 shows the variation of the system's poles as the freestream speed changes. As shown, the curve corresponding to the plunge mode transitions from stable to unstable at a speed of 11.4 m/s and thus this is taken to be the original, open-loop flutter speed.

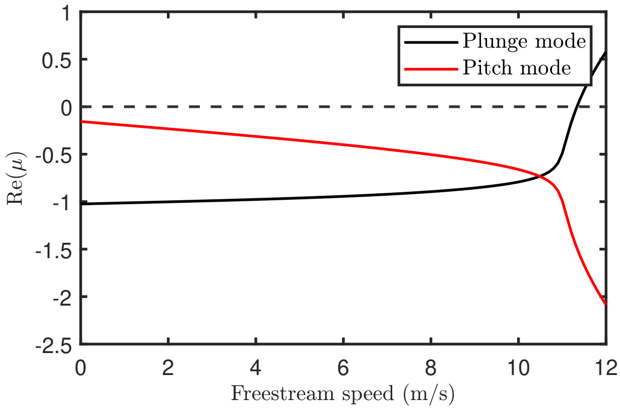
3.2 Numerical Example

The gain scheduling technique is now applied to the reference numerical model. Two objective functions are considered and the practicality of the method is discussed.

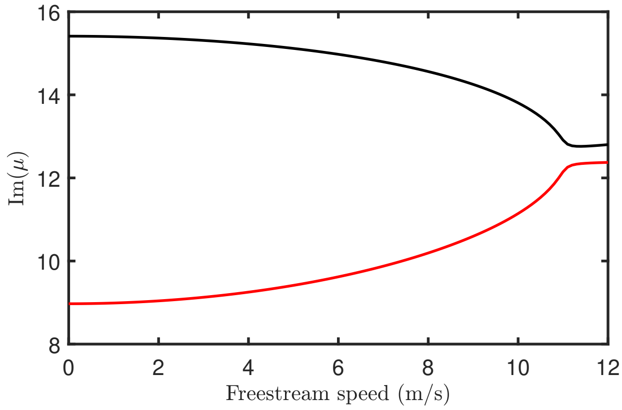
3.2.1 Iterative Control

Objective Function 1

In practice, one would determine the first control speed v_1 by gradually increasing the freestream speed and measuring whether the response had a sufficiently high level of damping that permits modal testing.



(a) Real part



(b) Imaginary part

Figure 2: Variation of the open-loop poles in the numerical model with respect to the freestream speed.

Numerically, however, this cannot be done and therefore at alternative approach is needed. In this work, a minimum damping speed v_{lim} is defined and corresponds to the speed above which the damping drops below 0.03. Across all control iterations, v_{lim} is the speed at which subsequent measurements are taken; it is considered impractical to measure receptance beyond this point.

To demonstrate the practical need for the frequency distance metric, the objective function is initially taken as

$$\rho_j = -\min\left(\zeta_j | \zeta_j \in \{\zeta_{j_i}\}_{i=1}^2\right) \tag{24}$$

This is equivalent to assuming α to be zero and implies that the objective function should only consider the minimum damping and not the frequency separation of modes. In this example, the constants in the gain constraints (Eq. 23) are set as

$$\frac{1}{15}\mathbf{\Lambda}_f = \mathbf{\Lambda}_g = \begin{pmatrix} 0.03^2 & 0 \\ 0 & 0.1745^2 \end{pmatrix}, \quad c = 5 * \frac{\pi}{180}$$

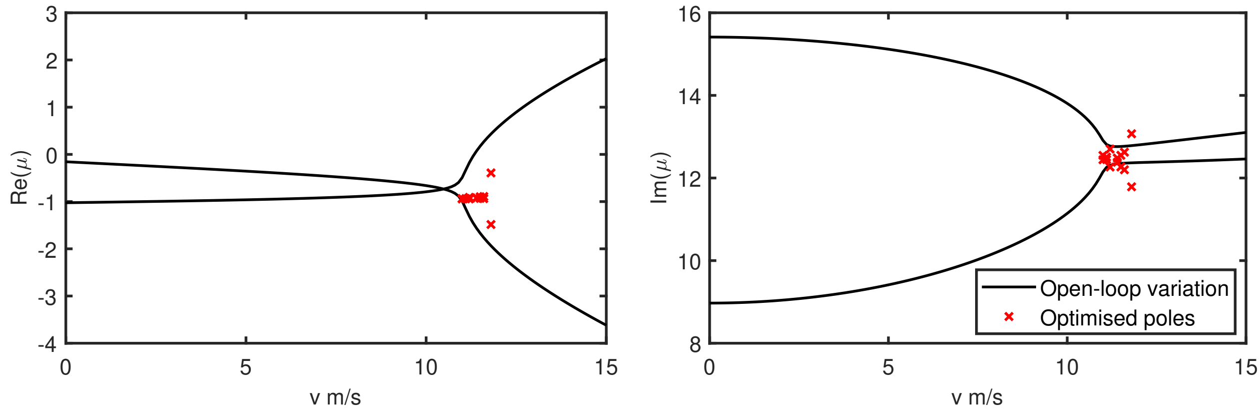
These values are based on a maximum control surface deflection of 5 degrees and uses the rough estimates of the maximum displacement and velocity in each degree-of-freedom from [10].

Table 1 shows the results of this first optimisation. Although this optimisation has successfully increased the flutter speed from 11.4 m/s to 12.4 m/s, it is unlikely that this would be practically possible. This is due to the very small changes in the iteration velocity v_{it}. In practice, noise in the measured receptances would dominate and thus a 0.1 m/s change in the freestream speed would: (i) be difficult to achieve experimentally with precision, and (ii) yield poles that vary very little, especially when measurement noise is considered. This is confirmed by Fig. 3, which shows the placement of the poles at each iteration step.

Table 1: Optimisation strategy one.

v_{it} (m/s)	v_{lim} (m/s)	v^* (m/s)
0	11.0	11.4
11.0	11.1	11.6
11.1	11.2	11.7
11.2	11.4	11.8
11.4	11.5	12.0
11.5	11.6	12.1
11.6	11.8	12.2
11.8	11.8	12.4

The stopping condition for this example is demonstrated in Table 1. At the 6th iteration (row 7), the limit



(a) Real part

(b) Imaginary part

Figure 3: Pole placement in optimisation 1.

speed v_{lim} becomes 11.8 m/s. In the subsequent iteration (row 8), v_{it} is equal to v_{lim} and thus the controller is unable to increase the minimum damping requirement above the measured speed.

Objective Function 2

From the first optimisation, it is clear that simply maximising the damping in all modes of the system does not necessarily push the flutter speed much higher, especially with conservative control constraints. Therefore, to remedy this, the objective function is now modified to

$$\rho_j = -\min\left(\zeta_j | \zeta_j \in \{\zeta_{j_i}\}_{i=1}^{2}\right) + \frac{1.47 \times 10^{-2}}{(\omega_{j_1} - \omega_{j_2})^2} \tag{25}$$

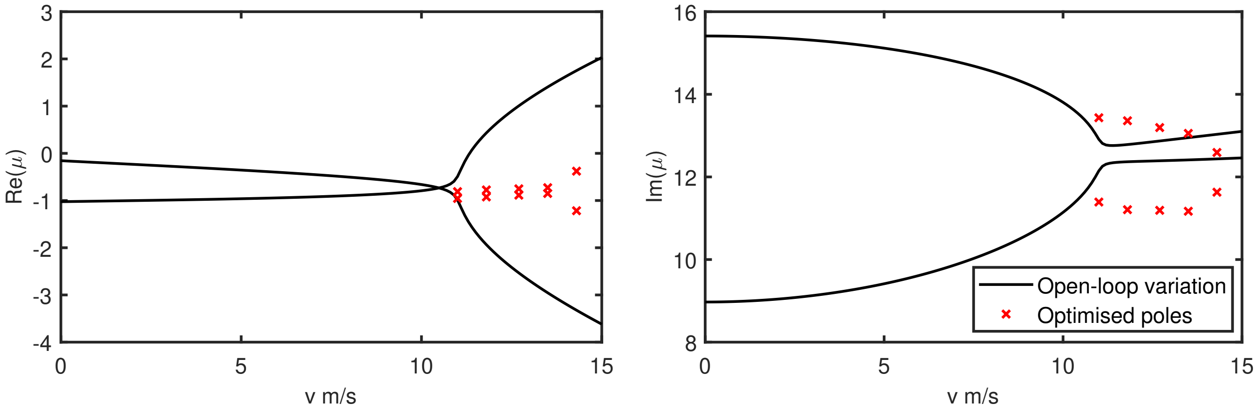
Here, the weighting constant α has been selected in such a way that the iterative method performs best. Table 2 shows the results of the new optimisation. The flutter speed now increases to a value of 14.8 m/s and thus the controller performs better, despite the control constraints remaining unchanged. This demonstrates the need to include a frequency distance metric; without it, the controller is likely to be sub-optimal and does not utilise the full control authority with the aim of increasing the flutter speed. Another interesting point is that this approach increases the speed sepearation between successive iterations. In practice, this is much more feasible and one could, potentially, take less measurements from the system and achieve a higher flutter speed in fewer steps. Figure 4 shows the placement of the poles in the second optimisation. As desired, the poles have a greater spacing and are now regularised in a much more desirable way.

Table 2: Optimisation strategy two.

v_{it} (m/s)	v_{lim} (m/s)	v^* (m/s)
0	11.0	11.4
11.0	11.8	12.2
11.8	12.7	13.1
12.7	13.5	14.0
13.5	14.3	14.8
14.3	14.3	14.8

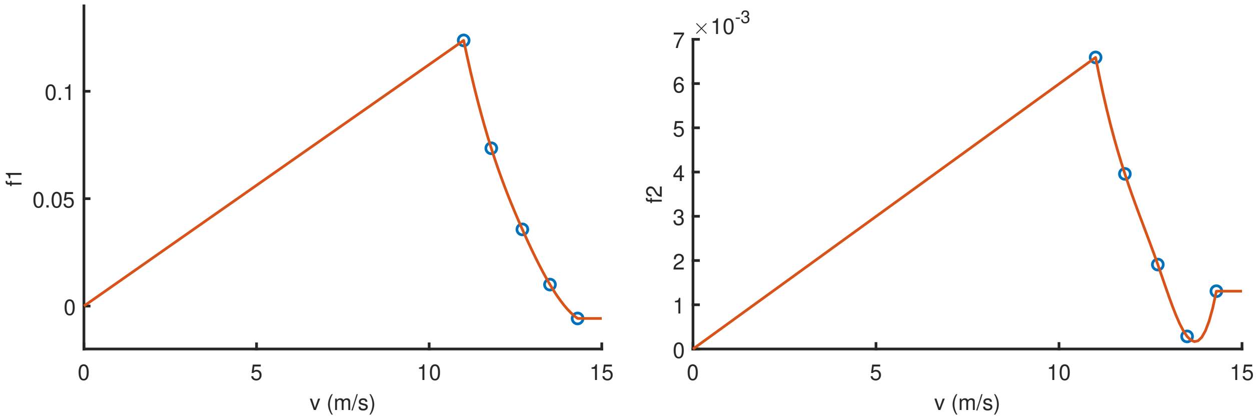
3.2.2 Gain Interpolation

The gain scheduling method is now applied to the results from optimisation 2. Figures 5 (a), (b), (c) and (d) show the computed control gains at each iteration velocity. The aim is to now interpolate between these points to yield a smooth transition of the gains for all freestream speeds. The result of this interpolation is shown in the same figure as a solid line.

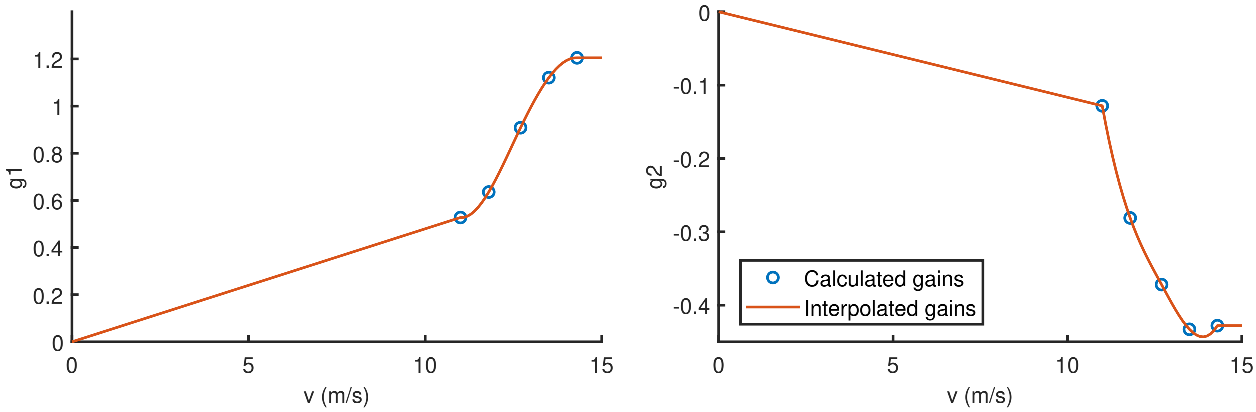


(a) Real part (b) Imaginary part

Figure 4: Pole placement in optimisation 2.



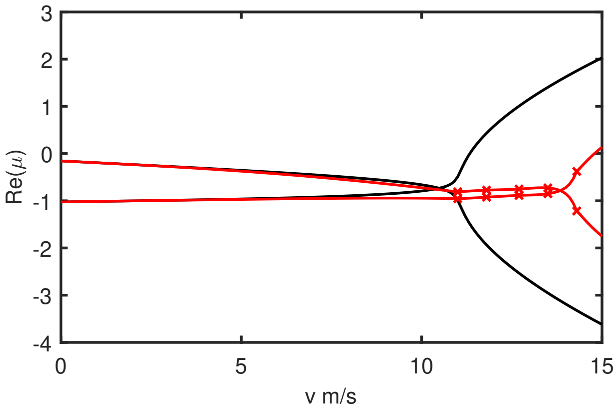
(a) f_1 (b) f_2



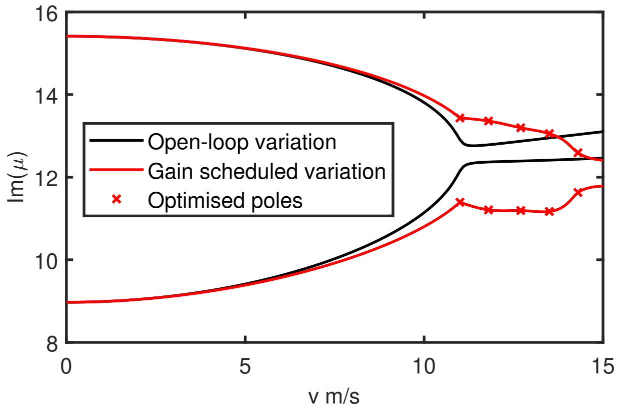
(c) g_1 (d) g_2

Figure 5: Computed control gains at the reference set of iteration speeds.

To verify and assess the final result, the interpolated, gain scheduled controller is applied to the system and, like before, the velocity is changed and the system's poles are determined. As shown in Fig. 6, the poles corresponding to the gain scheduled system pass through the poles found from the second optimisation. Furthermore, there is a smooth transition of the poles between the set of reference v_{it} speeds. It is noticeable, that the pole trends jump at speeds of 11 m/s and 14.3 m/s. This is due to discontinuities in the control gains. The avoidance of such discontinuities will be considered in future work.



(a) Real part



(b) Imaginary part

Figure 6: Variation of the gain scheduled poles.

It is important to note that, in this work, the inertia of the flap is not included in the numerical model. Therefore the flap has negligible control authority at low speeds due to the small aerodynamic influence and thus the dynamics of the system is modified only very slightly. In experimental systems, this may not be the case as the inertia of the flap can be significant. In such cases, it is suggested that interpolating the control gains from 0 m/s may be an inappropriate strategy and an alternative approach should be considered. This, however, is left as an area of future research.

4 Conclusions

This paper considers the extension of the Receptance Method to support gain scheduling in aeroservoelastic systems. An iterative control methodology is developed that allows the poles to be assigned using transfer function data at different reference speeds. The gains calculated at each successive reference speed are computed with the previously calculated gains active. In this way, receptances from the system can be measured above the open-loop flutter speed; this was not previously possible under the standard Receptance Method. At each of the reference speeds, the poles are placed optimally according to an objective function that considers both the damping and frequency separation of aeroelastic modes. A spline-based interpolation strategy is then used to determine a smooth variation in the control gains across the domain of all speeds, not just the reference values. The method is tested numerically and shows that the flutter speed can be increased, in an optimal fashion, provided that suitable weighting constants are chosen in the objective function. Future research may consider alternative strategies for the interpolation of the control gains such that discontinuities at the upper and lower limits of the reference speeds are avoided.

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