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Effect of Actuator Nonlinearities on Aeroservoelasticity

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It is well known that the design of flight control systems (FCS) for modern combat aircraft is seriously affected by the flexible modes of the aircraft structure. Frequently, because of a limited understanding of the array of complex issues involved, a very conservative approach is essential to achieve a FCS that will obtain flight clearance. We focus on the effect of actuator nonlinearities on the aeroservoelastic problem to promote greater understanding of the issues involved, thereby allowing the reduction of the degree of conservatism in the design. The effect of structural mode signals on the performance of the actuator at both low and high frequencies is examined. A mechanism is also described whereby the presence of a structural mode signal can generate both low- and high-frequency actuator output signal components. These can result in both further excitation of the structure and subharmonic aircraft response, as is demonstrated.

Introduction

FOR many years aeroelasticity has been a vital consideration in the aircraft design procedure, but more recently, the use of automatic flight control systems (FCS) with powered control surfaces has further complicated the problem. This interaction between the rigid body dynamics, structural dynamics, unsteady aerodynamics, and FCS of the aircraft is known as aeroservoelasticity.[1–3] The interaction between these disciplines can be represented as in Fig. 1, as adapted from Felt et al.[2] From the figure it is clear that the three outer arms of the interaction triangle can be considered as specific cases of the central aeroservoelastic interaction.

In essence, the problem of aeroservoelasticity exists because the excitation of the aircraft's structural modes can cause both oscillatory aerodynamic loads and oscillatory FCS demands resulting from the aircraft motion sensors being mounted to the airframe. These secondary responses can result in further excitation of the structural response (aeroelasticity and servoelasticity), as shown in Fig. 1.

As the structural efficiency of modern combat aircraft is increased and the use of fully digital FCS becomes commonplace, the possibility of an aeroservoelastic interaction taking place has become more likely, with many in-flight interactions being documented.[2,4–7]

At present, definite stability margins exist for the structural modes that must be met to clear an aircraft for flight.[8] These stability margins require certain gain and phase margins for the aircraft system as a whole at defined structural frequencies. To meet these requirements, it is current practice to incorporate notch and low-pass filters into the control system, which attenuate the structural-mode feedback to such an extent that the clearance requirements are satisfied.[9] The inclusion of such filters in the control system, however, incurs undesirable phase lag penalties at rigid body frequencies.

Generally, structural-mode filter design procedures are restricted by the reliability of the modeling and understanding of the aeroservoelastic problem.[9] To lessen the clearance restrictions employed, a greater level of understanding concerning the effects of the various system components on the problem must be achieved.

The four main components of the aircraft system that contribute to the aeroservoelasticity problem can be represented as in Fig. 2.

Much work has been done in developing an understanding of the elements independently, but little has been completed on examining the aeroservoelastic system as a whole and the way in which each element interacts with the others during a typical aeroservoelastic interaction.

Recent work in the area of aeroservoelasticity has concentrated on the development of analysis packages for the design of feedback filtering[10,11] and on improvements to the modeling of the unsteady aerodynamic effects.[12] In addition, work has also been completed on the effect of the digital nature of modern FCS on the aeroservoelastic problem.[6,13]

As one of the four main system components that contribute to the aeroservoelastic interaction, the effect of the servohydraulic actuation on the aeroservoelastic interaction has been largely assumed, with only the use of higher-order actuation models in the analysis of the aeroservoelastic system being investigated.[14,15] To date, no consideration has been given to the highly nonlinear nature of servohydraulic actuation system and to what effect this may have on the aeroservoelastic interaction. In addition, the effect of the structural mode feedback signals on the performance of the actuation systems has not been investigated.

It is the aim of this research to investigate the effects of each element of the aeroservoelastic system on the closed-loop performance of the aircraft. If a better understanding of the problem can be achieved, then it may be possible to relax the current clearance requirements for the structural modes. As part of this

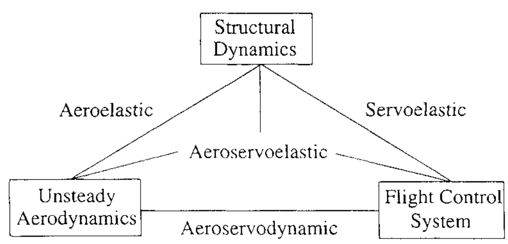

Fig. 1 Interaction triangle.

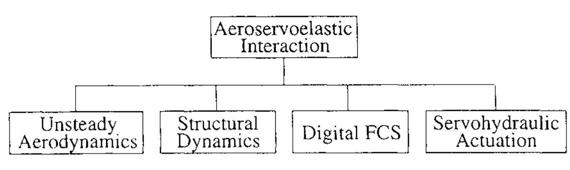

Fig. 2 Components of the aeroservoelastic interaction.

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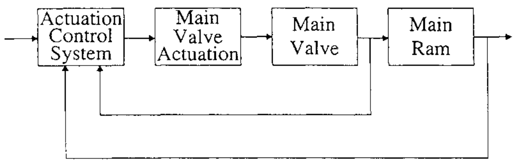

Fig. 3 Actuation system block diagram.

ongoing program, this paper examines in detail two elements of the aeroservoelastic problem. First, the effect of structural mode signals on the performance of the actuator will be investigated. In addition, the generation of harmonic and subharmonic signals within the actuator as a result of its inherent nonlinearities will be discussed, with the results applied to a full aircraft system model.

Nonlinear Actuation System Modeling

The basic components of a typical aircraft servohydraulic actuation system are shown in Fig. 3. In this case, the system is composed of four main blocks, namely, the actuator control system, the main valve actuation, the main valve block itself, and the main ram. The input to the system is in the form of main ram demand signals from the FCS, and the output is in the form of main ram position. The equations to describe the dynamics of each of these blocks in turn can be derived from modeling or testing of the actual hardware. The modeling of actuation systems is a large topic in itself, and the interested reader should refer to more specialized documents[16,17] for a more in-depth treatment.

Each of the four actuation system components contain considerable nonlinear elements, such as saturation nonlinearities representing current limits of the electrohydraulic servovalves. In addition, valve travel limits, valve backlash, valve friction, fluid compressibility, hysteresis, valve port profiles, and port flow equations add more nonlinearities to the model.

In this case, the actuation system model used is based on the Jaguar fly-by-wire (FBW) taileron actuator, which is representative of the actuator that is available for experimental verification of the results. This actuator was designed specifically for a digital FBW aircraft and is typical of actuators found on in-service aircraft.

The nonlinear model used in the analysis is derived from earlier analytical models[18,19] developed following testing of a typical actuator by the manufacturer.[20] Certain necessary assumptions were made for the nonlinear model to operate efficiently within the MATLAB/SIMULINK environment. A SIMULINK model of the nonlinear actuator was used for all analyses. The model contained a large number of the nonlinearities inherent in the actuator, including the valve port flow equations, valve travel limits, valve port shaping, and software rate limiting. The model, however, does not include factors such as ram loading, hysteresis, friction, and damping.

Effect of Structural Mode Feedback Signals on Actuator Performance

The role of the actuation system in the attenuation of structural mode signals can be easily seen from the magnitude of the frequency response of a linearized actuator model, as shown in Fig. 4. The attenuation produced at high frequencies by the actuation system can be seen to have a crucial effect on the propagation of these high-frequency structural mode signals around the closed loop. If the actuator provides a high degree of attenuation, then the aeroservoelastic problem will be reduced. Such a high level of attenuation, however, implies a lower bandwidth resulting in reduced performance. Relying on the attenuation of the actuators in solving the aeroservoelastic problem can also introduce serious effects on the stability of the rigid body aircraft as a result of structural modes falling within the bandwidth of the system.

In the following sections, the effect of high-frequency signals on this low-frequency performance and on the attenuation of the actuator at structural frequencies is investigated.

Linearity Boundary for Nonlinear Actuation System Model

The effect of the system's nonlinearities on actuator performance is important in the analysis of the total aircraft system's stability.

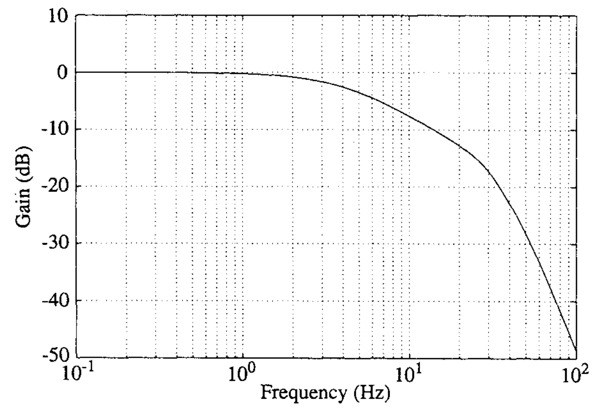

Fig. 4 Linearized actuator magnitude frequency response.

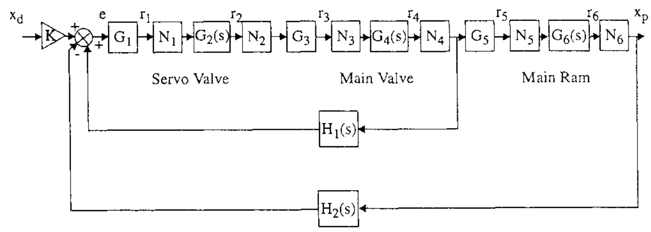

Fig. 5 Simplified actuator block diagram.

If the nonlinearities were not present, or the system was operating at such a point as to make their effect negligible, then the system stability can be readily assessed using classical linear theory.

The importance of being able to predict the region of linear behavior for an actuation system is therefore apparent, and this can be accomplished using simple linear theory.

Consider the block diagram of the actuation system for the actuator shown in Fig. 5, where the main valve flow equations have been linearized resulting in a linear transfer function between main valve position and main ram position. This process results in a model consisting entirely of linear elements and saturations.

For the output of ram position $x_p(t)$ as a function of demanded ram position, the closed-loop error transfer function can be produced for an operating point within the linear region, such that the saturation nonlinearities ($N_1, N_2, \ldots, N_6$) can be assumed to be simply equivalent to unity gain. Assuming this to be the case, the closed-loop error transfer function can be seen as

$$\frac{E(s)}{X_d(s)} = \frac{K}{1 + \{H_2(s) - [H_1(s)/G_5G_6(s)]\}\prod_{n=1}^{6} G_n(s)} = F(s) \tag{1}$$

Therefore, for example, the transfer function servovalve current $r_1(t)$ to demanded main ram displacement $x_{d(t)}$

$$\frac{R_1(s)}{X_d(s)} = G_1(s)F(s) \tag{2}$$

can be obtained easily. The transfer function only holds provided that none of the saturation limits are exceeded. Considering the servovalve current $r_1(t)$, for example, this signal must not exceed the level set by the nonlinearity N_1 in Fig. 5. The magnitude of input signal at which this level will be exceeded can be simply obtained from Eq. (2), for example, such that in the frequency domain

$$|x_d(j\omega)|_{\max} = \frac{|R_1(j\omega)|_{\max}}{G_1(j\omega)F(j\omega)} \tag{3}$$

which represents a frequency dependent linearity boundary for the system assuming saturation will occur at N_1 first and that all other saturation levels have not been reached. Repeating the steps for each nonlinearity in turn will build up a series of linearity boundaries for the system.

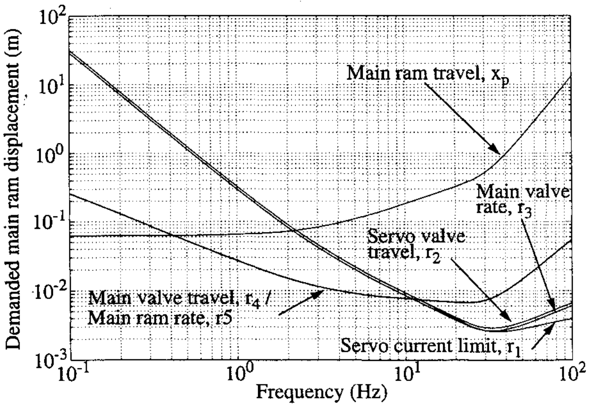

Fig. 6 Single-input linearity boundaries for simplified actuator model.

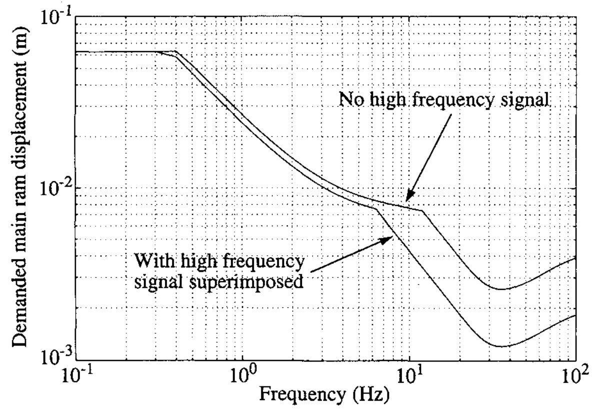

Fig. 7 Linearity boundaries for Jaguar FBW taileron actuator model with and without 50-Hz, 1.5e-3 m excitation signal.

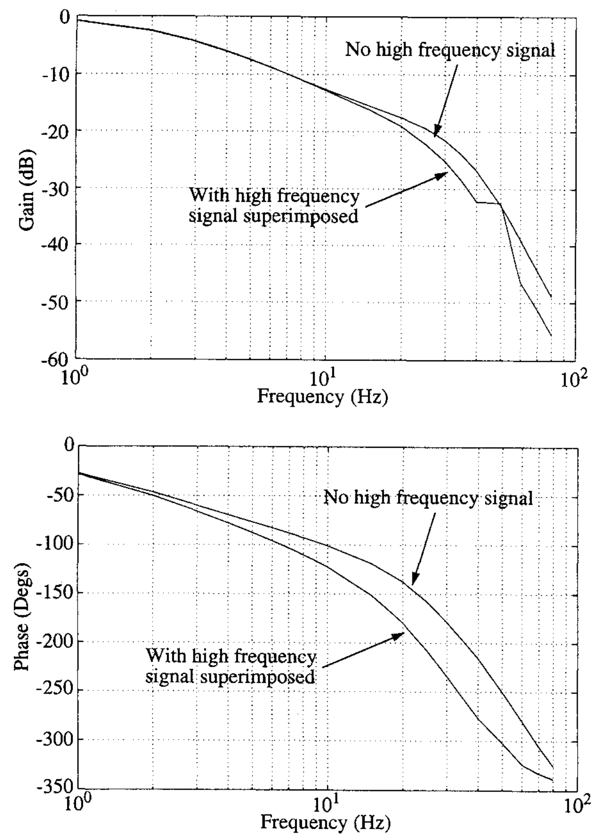

Fig. 8 Frequency response for nonlinear model with and without a 50-Hz, 1.5e-3 m excitation signal.

This procedure has been completed for the Jaguar taileron actuator model, as shown in Fig. 5 for each saturation in turn, with the resultant linearity boundary being as shown in Fig. 6.

The figure demonstrates that there exists a region in which the actuator will behave in a linear manner, the region being bounded by several curves depending on which of the component saturations of the actuation system is critical at the particular input frequency. For example, from Fig. 6, at low frequencies the critical limit is that of main ram travel, as would be expected. As the input frequency reaches approximately 0.4 Hz, however, the dominant limit becomes that of main ram rate/main valve travel, up to a frequency of approximately 10 Hz, where the limits of the servovalve become dominant.

When the actuator is subjected to a high-frequency input signal superimposed over a low-frequency signal, the performance of the actuator in terms of linear behavior would be reduced, since the presence of the high-frequency signal causes the margins from the linearity boundaries to be reduced. For example, suppose that the actuator was subjected to a high-frequency sinusoidal signal of certain amplitude. In responding to this signal, the actuator servocurrent, for example, might reach 50% of its limit value. This would leave only the remaining 50% of the limit current available for response to a lower frequency FCS signal before signal clipping would take place as a result of the saturation nonlinearity. The system operates in a nonlinear manner from this point on. The same reasoning applies for all of the saturations within the system model.

As a numerical example, for a high-frequency excitation signal of typical structural mode frequency 50 Hz and amplitude at actuator input of 1.5e-3 m, the linearity boundary for a second superimposed signal is as shown in Fig. 7, along with the original single-input linearity boundary. The linearity boundary for the case with the high-frequency excitation signal was produced by considering the reduction in the saturation limits available in response to the primary signal as a result of the presence of the high-frequency signal. As expected, the linearity boundary is lowered by the presence of the high-frequency signal, but only by very small amounts in the low-frequency ranges, where the main ram and main valve travel limits dominate. This effect is a result of the low-pass characteristics of the main valve and main ram. The problem then lies in the high-frequency ranges, where the high-frequency excitation signal reduced the linearity boundary significantly, and where a further high-frequency input signal could easily cause the servovalve limits to be reached and the region of nonlinear actuator behavior to be entered.

Effect of Structural Mode Signals on Low-Frequency Actuator Performance

The preceding analysis seems to indicate that the effect of the structural mode signals on the low-frequency performance of the actuator will be small, since the linearity boundary at low frequencies is changed little by the addition of the structural mode feedback signal.

The effect of structural mode signals on the performance of the actuator at low frequencies can be demonstrated by calculating the frequency response of the full nonlinear actuator model to low-frequency demand signals, when subjected to an additional high-frequency structural mode signal.

As a specific example, the frequency response of the nonlinear actuator model subjected to the earlier structural signal of frequency 50 Hz and amplitude 1.5e-3 m is shown as Fig. 8. In this case, the frequency response corresponds to a demanded actuator displacement of 1.0e-3 m, which is a typical demand amplitude for aircraft stabilization by the FCS. The frequency response was calculated from the time response of the nonlinear actuator model to the combined input signals. The two input signals were generated with zero phase angle such that reinforcement of the demand signal by the structural signal would occur for a demand signal of 50-Hz frequency.

It is clear from Fig. 8 that the structural signal did not greatly affect the gain of the actuator at low frequencies, verifying the expectation from earlier calculations. It is also clear, however, that the low-frequency actuator performance has been affected in terms of phase response. The presence of the structural signal induces extra phase

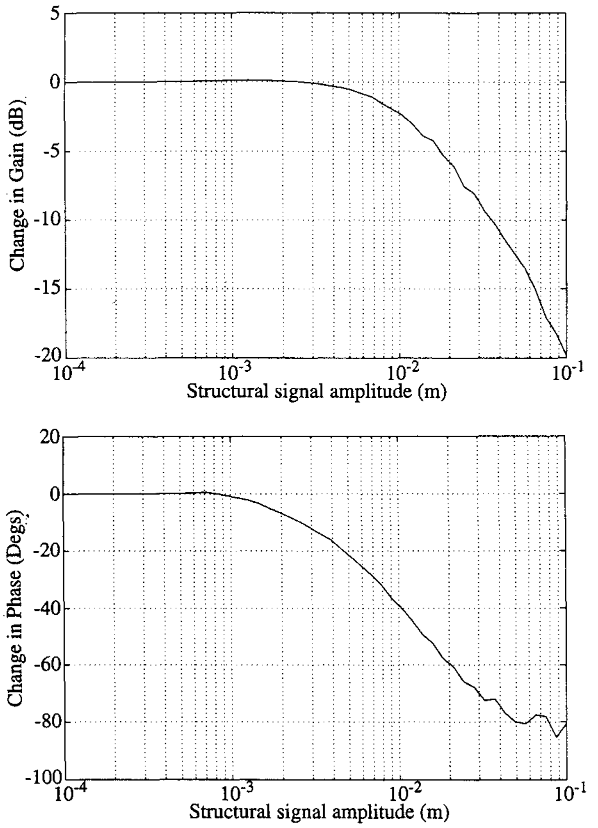

Fig. 9 Actuator gain and phase response changes for a 2-Hz, 1.0e-3 m demand signal and 50-Hz structural signal of varying amplitude.

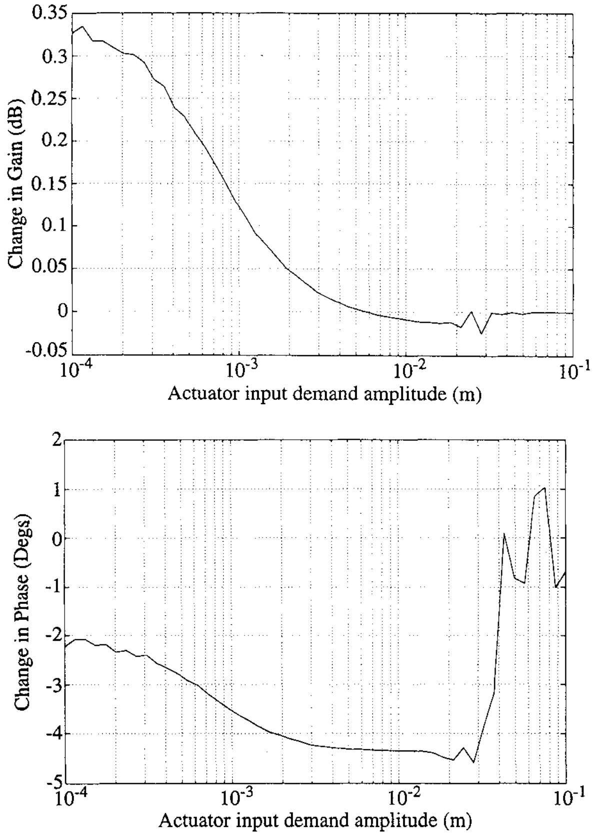

Fig. 10 Actuator gain and phase response changes for a 2-Hz demand signal of varying amplitude and 50-Hz, 1.5e-3 m structural signal.

lag into the system even though Fig. 7 predicts that none of the valve saturations will be reached under these operating conditions. This extra phase lag would be detrimental to FCS performance as a whole, although the magnitude of the effect will obviously be dependent on the magnitude of the structural signal and its frequency.

To demonstrate how the amplitude of the structural signal affects these results, the gain and phase response of the actuator for a demand signal of amplitude 1.0e-3 m and frequency was calculated for the nonlinear model in the presence of a 50-Hz structural noise signal of varying amplitude.

From Fig. 9, as the amplitude of the structural signal is increased, the effect on the performance of the actuator becomes more pronounced, as would be expected. Note, however, that it may be possible to specify a maximum level for the structural signal amplitude that could be tolerated for satisfactory aircraft control. This observation could in turn lead to a reduction in the attenuation requirements for the structural mode filters.

The preceding analysis has been for a particular amplitude of actuator demand signal, 1.0e-3 m, and no account had been taken of how the amplitude of this signal affects the results. This effect was then demonstrated by examining the actuator frequency response when subjected to a 50-Hz structural signal of amplitude 1.5e-3 m for varying amplitudes of actuator demand signal. This amplitude and frequency is representative of a filtered high-frequency structural feedback signal at actuator input. The results included in Fig. 10 demonstrate the changes in gain and phase for an actuator demand signal of frequency 2 Hz of varying amplitude as a result of the presence of a high-frequency structural mode signal of constant amplitude.

The results shown in Fig. 10 indicate that the affect of the structural signal on the gain is more pronounced for input demands of small amplitude. For large magnitude demand signals leading to saturation of the valve in their own right, the effect of the structural signal is minimal in terms of gain change, as would be expected. In terms of the effect of the structural signal on the phase response of the actuator, the results demonstrate that the change in phase is more pronounced for larger input demand signals. Once saturation of the valve travel limits is reached because of the combined input signal, however, the change in the phase response of the actuator as a result of the presence of the structural signal is minimal.

The overall effect of the input signal amplitude on the results shown in Fig. 10 is small, however, as the changes in gain and phase are only of the order of 0.4 dB and 5 deg, respectively. This, however, will be dependent on the structural signal amplitude and frequency.

Although the results presented here are limited in that they have only considered a single structural noise frequency and a single phase relationship between the two input signal components, they still demonstrate some interesting points. First, the addition of a significant phase lag to the actuator response as a result of the structural mode signal demonstrates how the problem of aeroservoelasticity can result in a reduction in the ability to control the rigid body aircraft itself. The effect of the amplitude of the structural signal on the results demonstrates, however, that a certain level of structural signal may be acceptable for satisfactory control of the aircraft. It should be noted, however, that these results apply for the case of a single structural signal only, and further investigation is required into the effect of multiple high-frequency signals on the performance of the actuator.

Effect of Structural Mode Signals on High-Frequency Actuator Performance

The preceding analysis demonstrates that provided that the structural mode signals are sufficiently small, the performance of the actuator to low-frequency demand signals is not seriously effected. As the amplitude of the structural signal increases, however, the performance of the actuator is affected, additional phase lag being introduced into the system.

Another important factor that requires addressing is the effect of the structural mode signals on the high-frequency performance of the actuator. It is the gain of the actuator at these frequencies that is assumed in the design of the structural mode filters. If the attenuation were to be reduced because of the presence of one structural mode signal, then the feedback filtering might no longer be sufficient at other frequencies.

In addition, work addressing the effect of the digital nature of a typical modern FCS[13] has demonstrated the presence of high-frequency signal components in the actuator demand signal. These component signals could also affect actuator performance when subjected to high-frequency structural mode signals, as well as having the ability to further excite structural modes or affect the performance of the actuator when subjected to low-frequency demand signals.

Figure 8 shows that the addition of the structural mode signal actually increases the attenuation of the actuator to high-frequency signals. Although this is an advantage in terms of structural mode attenuation, it is at the cost of extra phase lag in the response at rigid body frequencies. It seems sensible, however, to continue to apply the attenuation of the actuator when subjected to a single frequency input in the structural mode filter design procedures.

Effect of Subharmonic Generation on Aircraft Response

One aspect of the nonlinear nature of the actuation system that has not yet been addressed is that of the generation of subharmonics in the aircraft response. It is well documented that certain nonlinear elements when subjected to two input signals will result in an output signal with component frequencies below either of the two input signal frequencies.[21–23] If this is the case with aircraft actuation systems, then problems involving the control of the aircraft could result. If, for example, a structural mode signal interacted with a FCS demand signal to produce a control surface motion at a low frequency, then undesirable aircraft response could be induced.

Use of the Dual Input Describing Function to Predict Subharmonic Generation

The use of the single-input describing function (SIDF) and dual-input describing function (DIDF) is well documented in the analysis of nonlinear systems. In particular, the SIDF and DIDF methods have been successful in the analysis of the stability of nonlinear systems[22] and in the prediction of limit cycling.[21] Methods also exist for the calculation of the closed-loop frequency response of nonlinear systems.[24] The use of these techniques is limited, however, to simple systems of a low-pass nature, where the component signals generated by the nonlinearity can be neglected. In the case of this actuation system model, however, there are multiple nonlinearities, whose input signals may well have many component sinusoids.

It is still possible, however, to use the DIDF to predict the generation of output signal component frequencies for the nonlinear actuation system model.

According to the theory relating to the DIDF,[22] the output signal autocorrelation function for a general nonlinearity $n(x, y)$ subjected to two sinusoidal inputs can be expressed as

$$R_0(\tau) = \sum_{s=0}^{\infty}\sum_{k=0}^{\infty} \alpha_{sk}^2 \varepsilon_s \varepsilon_k \cos s\omega_a\tau \cos k\omega_b\tau \qquad (4)$$

where ε_n is the Neumann factor; $\varepsilon_n = 1$ for $n = 0$, and $\varepsilon_n = 2$ for $n = 1, 2, \ldots$.

For an input of the form $x + y$, where

$$x = a\cos\theta_a \qquad (5)$$

$$y = b\cos(\theta_b + \phi) \qquad (6)$$

the coefficient α_{sk} can be expressed as

$$\alpha_{sk} = \frac{1}{2\pi}\int_{-\infty}^{\infty} N(j\omega) j^{s+k} J_s(a\omega) J_k(b\omega)\, d\omega \qquad (7)$$

where J_n is the Bessel function of order n and $N(jw)$ is bilateral Laplace transform of the nonlinear characteristics.[22]

The importance of this derivation in this case is that it allows prediction of the output component frequencies. In the case of the actuator model, the multitude of nonlinearities make it difficult to predict the amplitude of the output signal components, but consideration of Eq. (4) shows that the output signal will contain frequencies dictated by the expression $\cos s\omega_a \cos k\omega_b$ for all integer combinations of s and k between zero and infinity.

Simple trigonometrical identities thus reveal that the output signal will contain components of frequency $(s\omega_a \pm k\omega_b)$.

Prediction of the component frequencies in the output from a nonlinear system, such as the actuation model used here, is therefore possible. One point to note, however, is that the coefficient α_{sk} that governs the amplitude of the component signals reduces to zero for saturation type nonlinearities[22] when $s + k$ is even. Thus, the signal component frequencies can be predicted in this case as being $(s\omega_a \pm k\omega_b)$ for all integer s and k between zero and infinity provided that $s + k$ is odd.

As an example, consider the nonlinear actuation model subjected to two sinusoidal inputs of frequency 3.05 and 7.1 Hz, the lower frequency being representative of a FCS demand signal and the upper frequency being representative of a low-frequency structural mode, such as the first wing bending mode.

From the preceding analysis, some of the lower-frequency output signal components can be predicted as shown in Table 1. From the table it is clear that the nonlinear operation of the actuator will result in the production of an infinite number of output component signals at frequencies both above and below the input frequencies.

Applying such input signals to the actuator model, with demand amplitudes of 5.0 mm at 3.05 Hz and 0.5 mm at 7.1 Hz, results in the power spectra of the output signal as shown in Fig. 11, with some of the intermodulation components marked. For the purposes of comparison, the output signal spectra for a linearized model is included as Fig. 12. Considering those component signals of high frequency the potential for excitation of the aircraft structural modes is obvious.

This example demonstrates that the highly nonlinear nature of the actuation system can result in subharmonic frequencies being generated as a result of the interaction between the FCS demand signal and any structural mode signal that is present at actuator input.

Effect of Subharmonic Components on Aircraft Response

As an example of how this might affect the aircraft system as a whole, consider the case where the nonlinear actuator model is incorporated into a full system model of the aircraft. In this case, the aircraft model is simply that of the rigid body aircraft with three control surface modes. The structural mode is represented by sensor noise, as suggested by Taylor et al.[25]

Table 1 Example actuator output component frequency

s	k	Frequency, Hz $(s+k)$	Frequency, Hz $(s-k)$
1	0	3.05	3.05
0	1	7.1	7.1
2	1	13.2	1.0
1	2	17.25	11.15
4	1	19.3	5.1
1	4	31.45	25.35

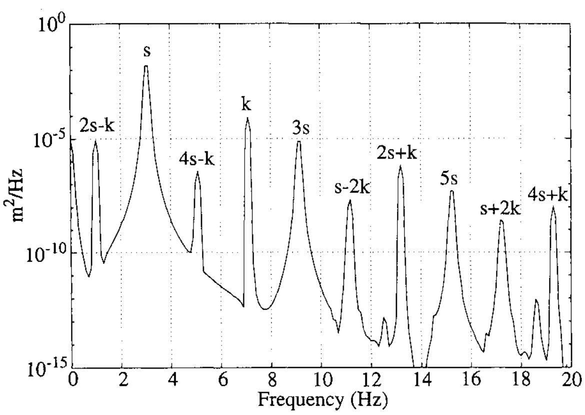

Fig. 11 Nonlinear model example output power spectra.

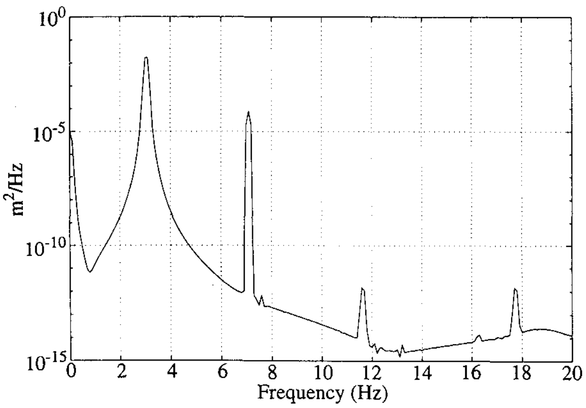

Fig. 12 Linearized model example output power spectra.

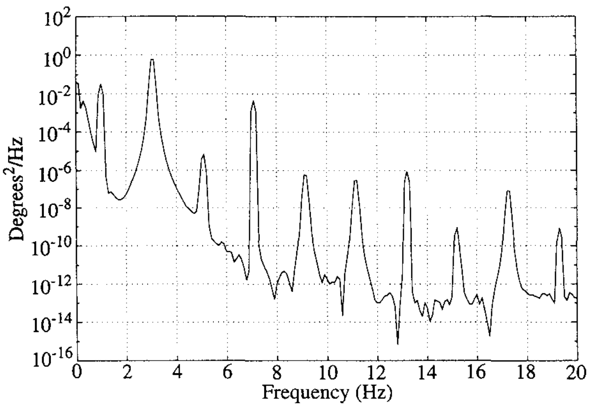

Fig. 13 Incidence angle power spectra.

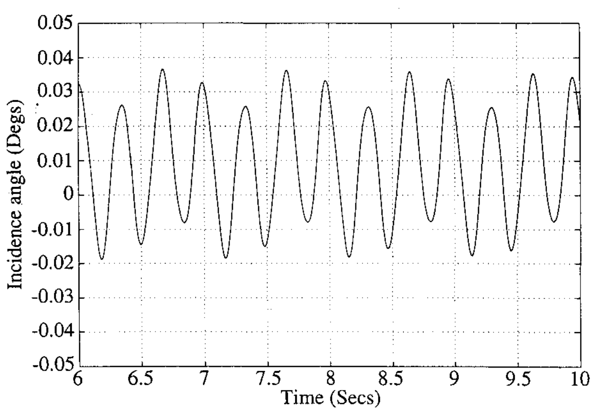

Fig. 14 Incidence angle time response.

Applying inputs described in the preceding section to the full system model results in a aircraft incidence power spectra shown in Fig. 13.

From Fig. 13, the creation of a 1-Hz actuator output signal component has resulted in aircraft response at this frequency, which can be seen in the incidence time response plot of Fig. 14. Comparing the power spectra plots of Figs. 11 and 13, it is clear that the low-pass nature of the rigid body aircraft attenuates significantly the higher frequency components, and the 1-Hz intermodulation component is still clearly visible in the response.

Effect of Higher Frequency Structural Modes on Subharmonic Generation

The preceding example concentrated on the effect of a low-frequency structural mode signal on the aircraft response. Suppose now that the structural mode was at a frequency of 31.5 Hz, while the FCS demand signal remained at 3.05 Hz. From the analysis, it would be expected that a component would again exist at 1 Hz as a result of $s = 10$ and $k = 1$ in the term $(s\omega_a \pm k\omega_b)$. If the power

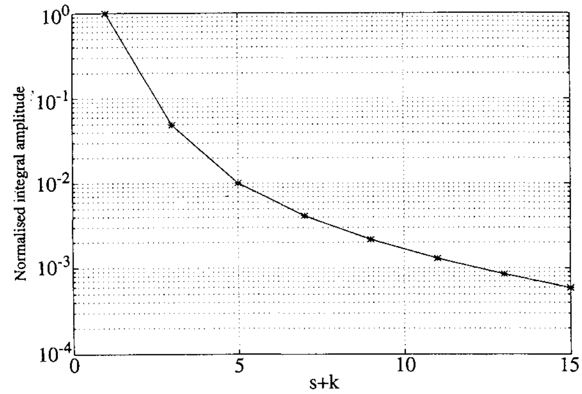

Fig. 15 Relative component amplitudes with increasing Bessel function order.

spectra for the output of the actuator is produced for these input conditions, the component that exists at 1 Hz is negligible, and as a result, the effect on the aircraft response is also negligible.

The reason for this effect lies in the amplitude coefficient α_{sk} of Eq. (7). From Eq. (7), it can be seen that the component amplitude is a function of the values of s and k through the order of the Bessel functions. Evaluating integrals of the form of Eq. (7) for increasing values of s and k for a saturation type nonlinearity, for example, results in Fig. 15. From the figure, it is clear that as the order of the Bessel functions is increased the component magnitude will decrease significantly.

For the numerical example, it can be seen from Fig. 15 that the 1-Hz component generated for input signal frequencies of 3.05 and 7.1 Hz ($s = 2$, $k = 1$) would have an amplitude approximately 40 times greater than the same component generated by input signals of frequency 3.05 and 31.5 Hz ($s = 10$, $k = 1$).

Hence, it is clear that significant subharmonic components will be generated only when the structural mode frequency is relatively low. This obviously depends, however, on the amplitude of the two input signals. In addition, input signals that are commensurate (ω_a/ω_b is a ratio of integers) cause further problems, as different combinations of s and k result in the same frequency component at output.

In addition, the amplitude of all components in the actuator output signal are governed by these considerations. It is possible then to apply these considerations when deciding which of the output signal components will be of significance.

Conclusions

The inclusion of nonlinear actuator dynamics in aeroservoelastic analysis has been shown to introduce some further problems regarding aircraft control. Although most aircraft flight control systems are designed to prevent actuator rate limiting, the existence of high-frequency structural signals has been shown to induce premature saturation of actuator components, the actuator having to effectively share its performance between the FCS demands and structural mode signals. As a consequence of this, the actuation system can begin to operate in a nonlinear manner due to the presence of the high-frequency signal, with its performance affected as a result.

The effect of these structural mode signals on the performance of the actuator at both low frequency (FCS demand) and high frequency (structural mode signals) has been demonstrated, and it has been shown that the existence of a structural mode signal may result in an additional phase lag being introduced in the system.

In addition, a mechanism has been described whereby subharmonic actuator response can be produced as a result of the presence of a structural mode signal. Incorporation of nonlinear actuator models into a full aircraft system model has shown that such a subharmonic response can result in a low-frequency aircraft motion in the presence of unfiltered structural mode noise. The production of these subharmonic responses is limited, however, by the frequency and amplitude of the structural signal; it being shown that only relatively low structural mode frequencies will result in significant subharmonic generation.

Finally, the same mechanism is responsible for the generation of high-frequency actuator output signal components that have the ability to further excite the aircraft structure.

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