Interactions Between an Aircraft Structure and Active Control Systems

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Analytical and experimental results from three different research programs in the field of active control are presented. Attention is focused on special problems related to the interaction effects between active control systems and aircraft structures. Furthermore, various viewpoints for the design of active control systems are illustrated and the extent to which adaptive control systems can contribute to an improvement of the stability margins of such systems is shown.

Introduction

THE implementation of active control systems in an aircraft is one of the most powerful means to increase its performance. Thus, it is evident that active control technology will have an increasing impact on the overall design of future aircraft. Active systems are considered to be highly beneficial in improving the rigid-body as well as elastic structural stability and dynamic response behavior of an aircraft.

The control configured vehicle (CCV) concept is a typical example of the influence of active control systems on the rigid-body (low-frequency) aircraft behavior and the benefits resulting therefrom. These benefits include, for instance, the fact that CCV technology allows the artificial augmentation of the longitudinal stability of an aircraft, which has an advantageous effect on its weight.[1]

Typical representatives of active control systems operating in the higher (elastic mode) frequency range are active flutter suppression systems (AFSS). These systems are especially convenient for improving the aeroelastic flutter stability behavior of fighter aircraft, the structual parameters of which are continually changed in a more or less significant manner due to the numerous external store configurations.[2]

These two examples indicate the extent to which active control systems can modify the stability characteristics of an aicraft by their interference with the passive aircraft structure. Unfortunately, not all of the interaction effects between aircraft and active control systems are necessarily beneficial to the aircraft's stability behavior. In the following discussion, attention will be focused on different types of more or less critical interactions that normally result from an incomplete active control system design. All interactions presented in the following sections were determined in a series of analytical and/or experimental investigations performed on different elastic aircraft structures.

Investigated Aircraft Structures

Since 1981, three different research projects have been conducted by the author in the field of active control. The first structure to be investigated for the layout of an active control system was a glider aircraft. The main objective of these purely analytical investigations was to apply and qualify a newly developed approach for the design of AFSS, the so-called "method of fictitious structural modifications."[3,4]

This method was also successfully applied to the AFSS design of a delta wing model structure. The efficiency of various analytically developed control laws were experimentally investigated in wind-tunnel tests.[5]

Quite sophisticated control laws have been recently designed for a swept-wing fighter aircraft model within the scope of a program undertaken by the Group for Aeronautical Research and Technology in Europe (GARTEur) called "Active Control Application for Flutter Suppression and Gust Load Alleviation."[6,7] The aim of this research program was to achieve flutter suppression and, simultaneously, to provide longitudinal and lateral stability augmentation as well as gust load alleviation by activating various active control systems implemented in the fighter aircraft. A typical control system investigated for the combined purpose of active flutter suppression, stability augmentation (SAS) and gust load alleviation (GLA) is depicted schematically in Fig. 1. All results indicated in the following sections are related to one of these three very different examples of application.

Active Control System Design Techniques

For the design of active control systems, various approaches can be used. In the case of AFSS, the classical design techniques are based either on the application of root locus methods,[8] frequency response methods,[9,5] or optimal control theory techniques.[10] Other less "conventional" design techniques such as Nissim's aerodynamic energy concept[11] or the method of fictitious structural modifications[3,4] can be applied as well. Control system design investigations result in the determination of the transfer behavior of the active control system's electronic compensation network(s) for defined characteristics of the actuators and sensors as well as for defined sensor locations (Fig. 1). Usually, different combinations of the sensor positions and compensation network characteristics are found suitable for controlling a certain problem. But, as will be shown here, various systems may differ considerably in their manner of interfering with the aircraft structure.

Working on the different aircraft structures previously described, various types of interaction between aircraft structure and active control systems were detected. For the sake of clarity we will classify these interaction types into four groups characterized by coupling between: 1) various rigid-body degrees of freedom (DOF), 2) rigid-body DOF and elastic modes, 3) elastic modes and rigid-body DOF, and 4) various elastic modes. Typical examples of interactions related to each of these groups are presented in the following sections.

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Interactions Between Rigid-Body Modes

In several of the tests performed on the fighter aircraft shown in Fig. 1, a control loop taking the pitch rate gyro output as a reference signal and acting on the inboard ailerons was used for the purpose of longitudinal stability augmentation and gust load alleviation.[6] As can be seen in Fig. 2, the control system significantly reduced the pitch rate level in the most critical phugoid mode. But, on the other hand, the control system caused an excitation of the short-period motion.

The explanation of this effect is rather simple. Due to the short distance of the inboard ailerons from the aircraft c.g., rather large deflections of these control surfaces are required to control the aircraft pitch in the phugoid motion. The lift thus induced by the larger aileron deflections supplies the heave motion in the short-period mode with positive energy that increases the heave and pitch amplitudes of the vibration in this mode.

This type of interaction is typical when using control surfaces that are not sufficiently effective in controlling "the" problematic mode. In this context, ineffectiveness means that the generalized aerodynamic forces induced by the control surface deflection in the critical mode are small compared to the corresponding terms generated in "other" modes. Accordingly, the wind-tunnel test results indicated that the taileron (horizontal stabilizer) was far more effective in controlling the aircraft pitch motion than the inboard ailerons.

The next example deals with effects resulting from the superposition of different active control system loops. In the case of the fighter aircraft previously mentioned, the tailerons as well as the wing spoilers were used for gust load alleviation purposes. As shown in Fig. 3, both of these control surfaces independently reduced the wing root bending moment. But the simultaneous activation of both control systems did not, as might be expected, lead to a further reduction of this value, but entailed an overall higher RMS of the wing root bending moment (Table 1).

This effect is due to the higher control system modal gain factor when both of the loops are simultaneously closed compared to the corresponding gain values in the case of individually closed loops. The (overly) high total gain value of the loops reduces the stability margin(s) and thus leads to a higher dynamic response of the structure. This explanation was confirmed by tests indicating that, for the conditions when both loops are closed, the gain factor of the loop could be reduced simultaneously by 50% without significantly increasing the RMS value of the wing root bending moment.

Interactions Between Rigid-Body and Flexible Modes

The rigid-body stability augmentation/gust load alleviation system described in the preceding section and acting on the inboard ailerons of the wing also interfered with the fundamental wing bending and torsion modes. The spectra shown in Fig. 4 clearly indicate that, due to the activation of the inboard aileron control loop, there is a noticeable increase in the wing root torsional moment in the first wing torsion mode. This is a clear indication of a reduction in the (modal) damping of this flutter-critical mode. Tests showed that the flutter speed of the fighter aircraft model dropped by about 7% when the inboard aileron control loop was switched on.

It can be concluded from these results that, due to the interference with a rigid-body active control system, the flutter speed of an aircraft can be considerably reduced. This is especially true in the case where the flutter critical mode has a flat damping characteristic with low damping values in the flutter stability diagram, which depicts the modal damping vs the air speed. In this context, it has to be mentioned that this type of flutter damping characteristic is typical for combat aircraft configurations with heavy external stores and for transport aircraft with high-aspect-ratio wings and heavy high-bypass-ratio engines.[12]

The excitation of elastic modes by active systems intended to control the aircraft rigid-body behavior is favored by the fact that the control of rigid-body aircraft motion, due to the high generalized masses involved, requires the generation of rather large generalized aerodynamic forces. The high efficiency of the required active control system allows that, despite the frequency spacing between rigid-body and flexible modes, the generalized aerodynamic forces induced by the control system in the higher frequency range be "large" compared to the small(er) generalized masses of elastic modes. Thus, these forces can greatly affect the stability of the elastic modes.

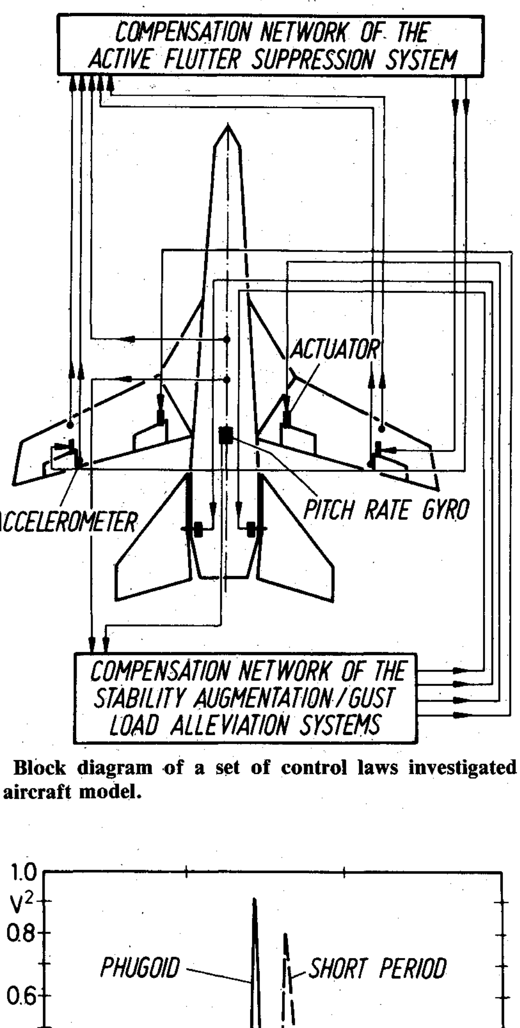

Fig. 1 Block diagram of a set of control laws investigated on a fighter aircraft model.

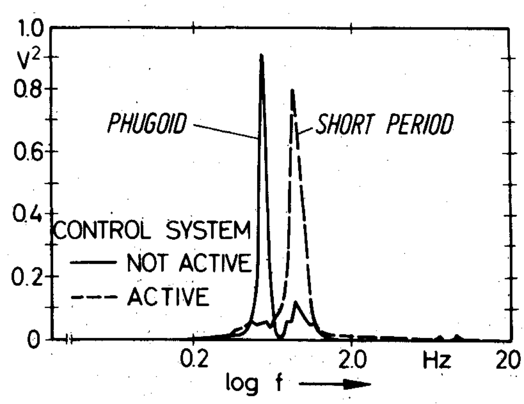

Fig. 2 Power spectrum of the aircraft pitch rate.

Table 1 RMS values of the wing root bending moment

Frequency range, Hz	0–2.5	0–8.0	0–20.0	2.5–20.0
Passive aircraft	0.141	0.162	0.162	0.0803
Spoiler active	0.0430	0.0815	0.0817	0.0696
Taileron active	0.0374	0.0828	0.0831	0.0743
Spoiler + taileron active (100% amplification)	0.0378	0.0825	0.0827	0.0738
Spoiler + taileron active (50% amplification)	0.0387	0.0856	0.0859	0.0767

Interactions Between Flexible and Rigid-Body Modes

Just as rigid-body mode control systems can interfere with the elastic modes, rigid-body instabilities can be excited by active control systems operating in the higher frequency range. During the analytical layout phase of the AFSS depicted in Fig. 1, the rigid-body heave and pitch modes of the aircraft were considered in all the flutter calculations. The results indicated that an adverse coupling between the first wing bending and rigid-body heave mode could result from the implementation of an AFSS, leading to the destabilization of the rigid-body mode. The calculated results were confirmed by the subsequent wind tunnel tests.

Due to the different order of magnitude of the generalized masses related to the rigid-body and elastic modes, the excitation of the rigid-body modes by a control system operating in the higher frequency range is generally not as easy as vice versa. Special care, however, is required with regard to a flexible/rigid-body mode coupling in the case of an aircraft featuring relaxed rigid-body stability characteristics.

Interactions Between Flexible Modes

The design of active control systems for the alteration of the stability behavior of flexible modes requires "some" engineering intuition, since these systems usually have to operate within a narrow frequency band. Especially in the case of a high-eigenfrequency density in the neighborhood of the mode(s) to be controlled and a not fully symmetric aircraft from the structural point of view, a very careful design of the active control system is imperative.

A problem encountered while designing the AFSS of the fighter aircraft shown in Fig. 1 was the excitation of the first vertical fuselage bending mode at 10 Hz by the active system, which acted mainly on the first wing torsion mode at 5.5 Hz. Analytical investigations indicated that, by adding additional filtering elements to the electronic compensation network of the AFSS, excitation of the fuselage bending mode could be avoided, but the artificial flutter speed dropped considerably. The problem was solved by adding a fifth sensor feedback signal (Fig. 1) at the AFSS. The signal is emitted from an accelerometer located on the aircraft fuselage at a point with a high amplitude in the fuselage mode, but very small amplitudes in the two flutter-critical modes.[4] By means of this precaution, the modal sensor feedback signal in the fuselage bending mode was completely nullified and this critical mode was stabilized.

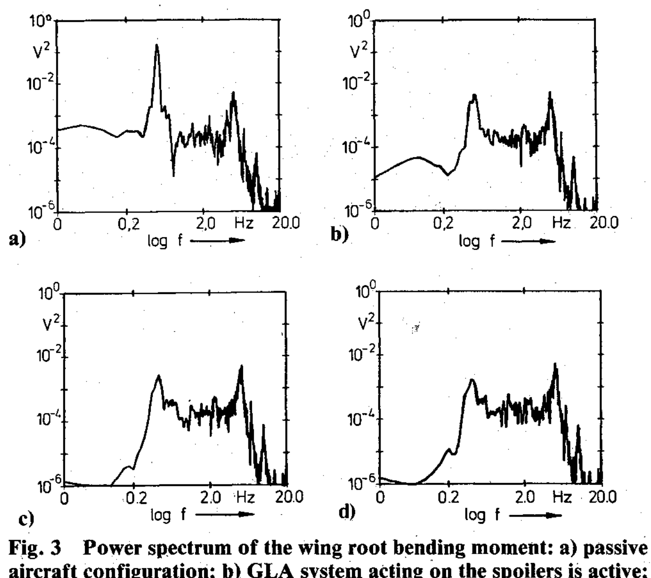

Fig. 3 Power spectrum of the wing root bending moment: a) passive aircraft configuration; b) GLA system acting on the spoilers is active; c) GLA system acting on the taileron is active; d) GLA systems acting on the spoilers and on the tailerons are active.

Interactions with an Actuator Mode

During some of the tests,[5,7] a coupling between the active control system(s) installed in the aircraft and the actuator mode(s) was identified. These interactions may occur during wind-tunnel tests in a somewhat unexpected manner. This is true especially when the dynamic behavior of the control surface degrees of freedom was not investigated during the ground vibration test—because of the generally wide frequency spacing between the control surface degrees of freedom and the eigenfrequencies of the first elastic modes—and/or when the more or less complex dynamic behavior of the actuators was not properly considered in the calculations.

As an example of this coupling effect, Fig. 5 shows the closed-loop frequency response at a supercritical air speed of an AFSS design for the case of the fighter aircraft shown in Fig. 1. The first high and narrow peak at 6 Hz is related to the flutter mode. The second broad peak at 42 Hz is attributed to the highly damped actuator mode. The high response in this mode must be avoided even if it might not cause a stability problem, since this high-frequency response of the actuator requires considerable hydraulic power. Due to the normally wide frequency spacing between the actuator mode(s) and the mode(s) to be controlled, such a high-frequency actuator response can be reduced considerably by adding a low- or bandpass filtering element to the control loop compensation network.

Instability Related to the Active Control System Compensation Network

Perhaps the most interesting type of instability from the point of view of the engineer primarily involved in structural dynamics are the instabilities related to the control system compensation network. These instabilities appear at frequen-

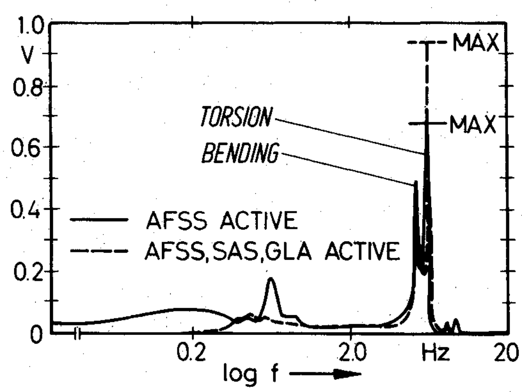

Fig. 4 Spectrum of the wing root torsional moment.

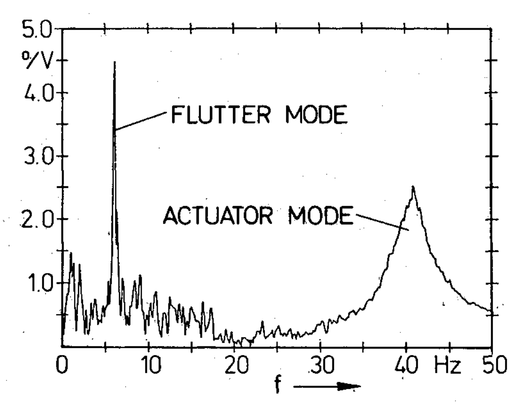

Fig. 5 Measured frequency response of the AFSS control loop at a supercritical air speed.

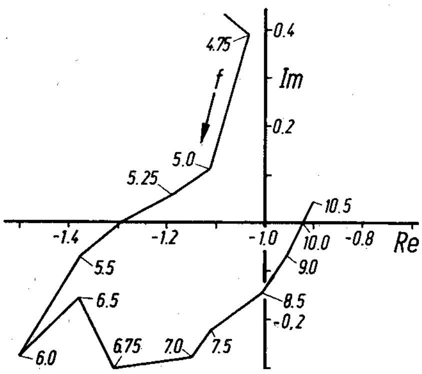

Fig. 6 Experimentally determined supercritical Nyquist stability plot.

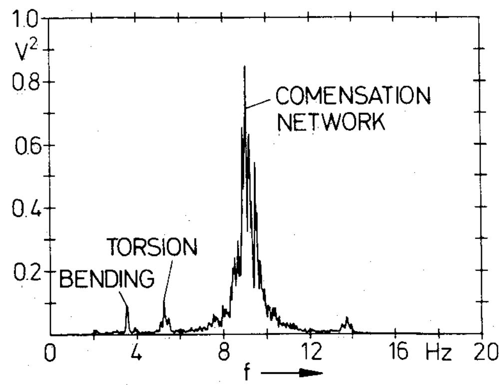

Fig. 7 Power spectrum of the control surface deflection angle.

cies that cannot be attributed to any of the aircraft rigid-body or elastic structural modes.

In the case of the delta wing structure[5] with elastic mode eigenfrequencies at 3.4, 6.5, 13.4, 16.7 Hz, ..., a control system "instability" was detected in the 9.5 Hz frequency range for one of the control law cases. A measured supercritical Nyquist stability diagram (Fig. 6) of the flutter control loop, i.e., at an air speed in excess of the open-loop flutter speed, indicated that this instability was caused by a small amplitude margin in the 10 Hz frequency neighborhood.

This instability entailed moving the control surface (flap) mainly at a frequency not corresponding to the critical flutter frequency. The power spectrum (Fig. 7) of the control surface deflection, measured for the case of the closed-loop system, suitably depicts the excessive control surface motion at 9.5 Hz.

Electronic and Geometric Filtering

All types of undesirable interactions between rigid-body or flexible structural modes and the implemented active control system(s) must and generally can be avoided by means of electronic and/or geometric filtering precautions. Electronic filtering allows 1) the separation of "low-" and "high"-frequency ranges by means of low- or high-pass filters, 2) the separation of the mode(s) to be controlled from other modes outside a neighboring frequency band by means of bandpass filters, and 3) the suppression of the feedback control signal in well-defined modes by means of notch filters. It would, however, be a mistake to assume that any (induced) instability problem can be solved merely by inserting electronic filtering elements into the electronic compensation network. While electronic filtering is a powerful means of preventing abnormal mode excitation, it generally has an unfavorable effect on the transfer behavior of the compensation network in the frequency range of the mode(s) to be controlled.

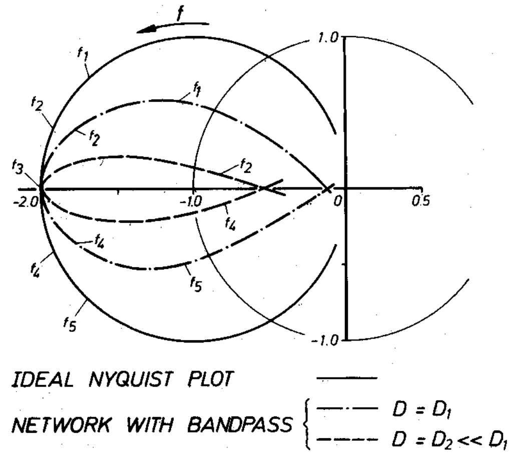

Fig. 8 Various shapes of supercritical Nyquist stability plots.

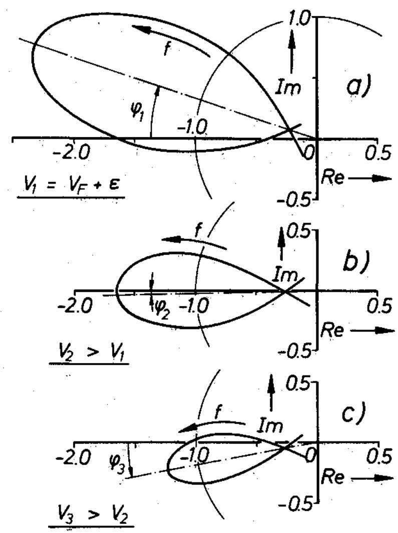

Fig. 9 Change in the shape of a supercritical Nyquist plot with increasing speed.

Thus, as an example, the implementation of a bandpass filtering element into the compensation network of an AFSS would squeeze the supercritical Nyquist "circle" related to the unstable flutter mode if its corner frequency f_0 is adjusted to the critical frequency of flutter f_F. The plots of Fig. 8 indicate that the lower the damping of the bandpass element, and thus the more distinct the bandpass characteristic, the lower the phase margins of the control system with regard to the unstable (flutter) mode. This example typically illustrates the manner in which electronic filtering elements generally reduce the robustness of active control systems.

The technique of geometric filtering can avoid this problem. In this context geometric filtering means that, given the skillful placement of the (additional) sensor(s) on the structure, the modal sensor feedback signal is nullified in well-defined modes. These modes can then be considered, at least in an initial approximation, as being "out of the loop" and thus not affected by the active control system. Geometric filtering techniques rely on the choice of adequate sensor positions. A primitive but efficient procedure for the determination of "optimal" sensor positions has been outlined in Ref. 4.

The fundamentals of the method are as follows. Assume that a flutter instability is caused by the coupling of two elastic modes (e.g., first wing bending and torsion). In order to control these two modes efficiently, the sensors must be located at positions on the aircraft structure that exhibit large (normalized)

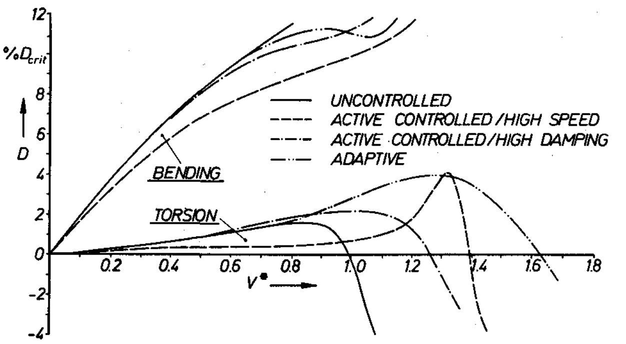

Fig. 10 Damping characteristics of the bending and torsion modes involved in the flutter for different AFSS designs.

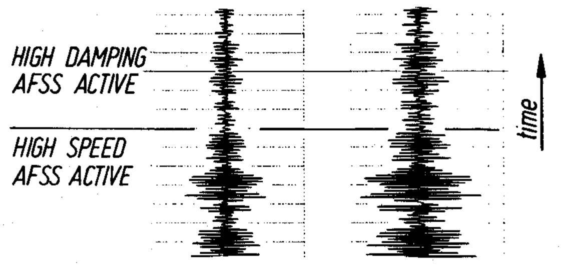

Fig. 11 Dynamic acceleration response of a structure for the case of high-speed or high-damping AFSS designs.

amplitudes in these two modes, but comparably small amplitudes in the "remaining" modes in order to avoid adverse structural/control system interaction effects. To detect the best-suited sensor locations, the following values are calculated for each of the numerous accelerometer positions from the ground vibration test:

$$H_{1i} = |\phi_{i1}| \Big/ \sum_{r=1}^{n-1} |\phi_{ir}| \tag{1}$$

$$H_{2i} = |\phi_{i2}| \Big/ \sum_{r=1}^{n-1} |\phi_{ir}| \tag{2}$$

$$H_{3i} = (|\phi_{i1}| + |\phi_{i2}|) \Big/ \sum_{r=1}^{n-2} |\phi_{ir}|, \quad (i=1,2,...,N) \tag{3}$$

where $|\phi_{i1}|$ and $|\phi_{i2}|$ are the absolute values of the deflections of the ith accelerometer in the two eigenmodes to be controlled, $|\phi_{ir}|$ the absolute value of the deflection at this ith point in the rth "remaining" eigenmode, n the overall number of eigenmodes considered in a frequency band of primary importance, and N the total number of accelerometers located on the aircraft structure during the ground vibration test.

Adequate sensor positions are characterized by large values of H_{3i} as well as of H_{1i} and/or H_{2i}. It is particularly easy to detect the largest values when all H_{1i}, H_{2i}, and H_{3i} are normalized with regard to their corresponding maximum values $H_{1\max}$, $H_{2\max}$, and $H_{3\max}$, respectively.

The practical application of this routine revealed that 1) of the numerous accelerometer positions considered in the ground vibration test, only a small number of sensor locations is suited for control purposes, and 2) adequate sensor positions exist which are not recognized ad hoc by pure engineering intuition. To answer the question of when to apply geometric or electronic filtering techniques, the following rules of thumb can be formulated:

1) Avoid excessive filtering (with large negative phase shifting) in the immediate vicinity of the mode(s) to be controlled, if possible.

2) Use electronic filtering primarily to separate modes in the case of a "wider" frequency spacing.

3) Geometric filering is recommended whenever the mode(s) to be controlled and other critical modes are located in a "narrow" frequency band.

Active Control System Stability

This section deals with the interrelation between the stability margins of active control systems, the modal structural damping characteristics, and the dynamic response behavior of the aircraft structure. Nyquist stability diagrams, as shown in Fig. 9, alter their shape as a function of the air speed, even in the case of a well-defined control law and a given aircraft structure. A variety of investigations indicate that, with increasing speed, the supercritical Nyquist "circles" of artificially stabilized modes rotate in a counterclockwise direction around the origin in the complex plane and their diameters decrease.

Assume now that an AFSS is to be designed. The system is stable within the supercritical condition, the Nyquist loop encircles the point $(-1,0)$ once in a counterclockwise direction. Maximum flutter speeds with the controlled system can thus be obtained if, just above the flutter speed of the uncontrolled aircraft, the Nyquist loop barely encircles the point $(-1,0)$ with its lower part (Fig. 9a). With increasing speed, the entire Nyquist plot will now rotate in a counterclockwise direction and contract (Fig. 9b). Finally, at the flutter speed of the controlled aircraft, the Nyquist plot will be intersected in its upper part by the point $(-1,0)$ (Fig. 9c). Due to the small phase margins at nearly all air speeds, such an AFSS, characterized by a maximum flutter speed in the case of the actively controlled aircraft, will exhibit poor damping characteristics of the flutter-critical mode.

As an illustrative example, Fig. 10 depicts in the form of dashed curves the results obtained from a flutter calculation performed on the model delta wing structure[5] fitted with a high-speed AFSS design. The incease in the damping of one of the (two) modes primarily involved in the flutter case are typical for high-speed AFSS designs. Because of the small phase margins in a broad speed range, this AFSS design is of no practical use.

The design of an AFSS with satisfactory stability margins and thus good damping characteristics requires the Nyquist plot of Fig. 9a to be turned counterclockwise by the angle φ_1. But due to the further rotation of the Nyquist "circle" with increasing air speed, this high damping AFSS will never reach the top flutter speed of the high-speed AFSS design (Fig. 10).

High speed and high damping can, however, be achieved when making use of an adaptive AFSS. This means that the parameters of the electronic compensation network (especially the amplifier and phase shifting characteristics) of such an adaptive control system have to be constantly readjusted in accordance with a well-defined function of one or more significant parameters. In the special case of an AFSS, this significant parameter could be the dynamic pressure or the air speed. This allows the critical Nyquist "circle" to be "frozen" in the complex plane at all air speeds in a position featuring the best amplitude and phase margins. The results obtained from the flutter calculations under consideration of the adaptive AFSS are also depicted in Fig. 10.

It is not only important with regard to the stability and robustness of active control systems to achieve satisfactory margins, but also with regard to the dynamic response behavior of the actively controlled structure. Since high margins automatically entail high damping, the dynamic response behavior of an aircraft structure will directly depend on the margins of the implemented active control system(s).

As an example, Fig. 11 depicts the measured dynamic response of two accelerometers located on the delta wing model structure[5] for flight in a continuous nonperiodic wind-tunnel gust environment. In the lower part of the figure, a high-speed AFSS was switched on, but then the control was turned over to a high-damping AFSS that considerably reduced the dynamic response of the model to the gust excitation.

Since a high-damping AFSS can significantly reduce the dynamic structural response, e.g., the wing root bending moment, these systems can be considered and used for the alleviation of gust loads in the flutter-critical modes of the wing, which are normally the first wing bending and torsion. This similarity in the design of a (flexible mode) gust load alleviation system and a high-damping AFSS, both operating in the higher-frequency range, also exists in the rigid-body mode frequency range between the designs of gust load alleviation and stability augmentation systems.[6]

Conclusion

The numerous results from analytical and experimental investigations presented here indicate that active control systems can considerably change the dynamic behavior of aircraft. This is the reason for implementing active control systems into aircraft. On the other hand, a variety of adverse coupling effects between active control systems and the aircraft structure can result therefrom. The most "dangerous" interactions may be those leading to coupling between rigid-body and elastic modes and vice versa, since they completely interconnect the "low"-frequency range of flight mechanics to the "high"-frequency range of aeroelasticity. Unless specialists from both of these fields work together closely when designing active control systems, it could happen that, for instance, 1) a gust load alleviation system intended to reduce the loads in the rigid-body modes interferes with the elastic modes and (considerably) reduces the aircraft flutter speed, or 2) an active flutter suppression system operating in the higher-frequency range induces an instability in the rigid-body modes. Caution is also required in the case that the modal parameters of the control surface degrees of freedom are not sufficiently known. This recommendation also applies if these data were determined in a ground vibration test, since the actuator transfer characteristics are usually dependent on the amplitude, frequency, and preload.[13]

With regard to the broader application of active control technology in future aircraft, it will be necessary to set guidelines concerning the stability margins required for the different types of active control systems. Apart from the degree of risk inherent in each active system itself, which greatly depends on whether the control system is operated in a sub- or supercritical mode, the possible interaction effects between active control system(s) and the aircraft structure will certainly have to be considered in the margin requirements. Moreover, further research is necessary to investigate the influence of the (rigid-body) active control systems on the aircraft flight qualities that directly affect the pilot/aircraft control system loop.

Despite the many possible problems outlined in this paper for the sake of their documentation, it can be stated that, in the long run, active control technology certainly is and will remain an excellent means of improving aircraft performance. As, for example, in the case of the aircraft shown in Fig. 1, in which an uncontrolled configuration exhibited instabilities at 17 m/s for Dutch-roll motion, at 31 m/s for phugoid motion, and at 40 m/s for flutter, it was possible to achieve flight in a severe nonperiodic symmetric or asymmetric wind-tunnel gust environment at an air speed of 55 m/s by means of the implementation of various active control loops.[7] But from the numerous investigations performed in the past, it has also been shown that such powerful active control systems require special care with regard to their design, reliability, and maintenance.

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