# Engineering Notes

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## Inflight Aircraft Vibration Modes and Their Effect on Aircraft Radar Cross Section

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### Introduction

THIS Note describes a short feasibility study of the identification of aircraft by type through the modulation of aircraft radar cross section (RCS) by elastic inflight vibration modes. Three aircraft were chosen as test cases: a variable-geometry fighter/bomber (hereafter called Type A), a swept-wing fighter (Type B) and a relatively straight-winged fighter (Type C). The identification of aircraft by this scheme requires unique elastic mode shapes and/or frequencies for each aircraft; these modes must remain distinct as the loads and airspeed are varied. The amplitude of vibration in these modes must be comparable to the wavelength of the radar (of the order of a quarter wavelength) so that the unique vibration characteristics would cause an observable unique dynamic RCS modulation.

### Inflight Frequencies and Mode Shapes

The natural frequencies and modes of the aircraft structure were provided by the program FACES.[1] The structure is modelled as an assembly of beams with rotational and translational inertias and interconnected by torsional and linear springs. The aerodynamic forces considered were based on strip theory and act on the wing only. The wing bending and torsion and the fuselage bending modes were considered to be the only relevant degrees of freedom. The elastic motion is not synchronous, i.e., different points on the wing and fuselage are not in phase with each other (Fig. 1).

The three aircraft were modelled with the internal (fuel) and external (stores) loads as parameters and at airspeeds of 0 and 500 kts. The wing sweep angle on Type A was also varied. Some generalizations drawn from the results are that the variation of mode shape and frequency 1) with airspeed and with wing sweep (for Type A) is generally modest and could be accounted for if either occurred separately; and 2) with fuel and stores load is so large that unscrambling the modes is difficult.

Certain load configurations of Type B and C can mimic the frequencies of Type A; therefore, to be recognizable, a Type A mode would have to have a unique feature such as large tail motion (not studied here).

### Amplitude of Vibration

The amplitude of vibration must be comparable to the radar wavelength to be detectable. As the minimum radar wavelengths are constrained by upper limits on achievable radar frequencies, there is a lower limit on observable amplitudes. The vibratory modes of the aircraft are excited by atmospheric turbulence. About five percent of a typical flight path contains gusts of 2 ft/s or more recorded at least every 10 s.[2] Thus, a 2 ft/s gust was used to establish the vibration amplitude that could be expected routinely.

Idealized cases were studied to establish typical amplitudes. The elastic response in the wing-bending modes to a sharp-edged 2 ft/s gust was calculated following Bisplinghoff, et al.[3] The wing-tip deflection ranges from ¾ in. (Type B) to ⅛ in. (Type A). The bulk of this response is in the first mode (Fig. 2). The rigid-body plunging response to continuous turbulence is also typically less than 1 in. rms displacement. The vibration modes were scaled accordingly and harmonic motion in the first wing-bending mode was used in the radar-scattering model.

### Radar Cross-Section Studies

The radar-scattering model of the aircraft consists of an ensemble of appropriate geometrical shapes of known scattering properties. Thus the nose is modelled by a paraboloid, the wings and horizontal tail by rectangular plates, the fuselage by a cylinder and the engine intake and exhaust ducts by circular cavities. These scatterers are replaced by scattering centers located at various points on the aircraft structure and with equivalent scattering areas. This approach has been successful in theoretical RCS calculations.[4]

The RCS of the non-vibrating aircraft, called the static RCS, has been obtained in several ways:

1) $\sigma_p$, the static RCS by relative phase

$$\sigma_p = \left| \sum_{j=1}^{6} (\sigma_j)^{1/2} \exp(\beta_j) \right|^2$$

where $\sigma_j$ is the RCS of the $j$th component and $\beta_j$ is its relative phase angle.

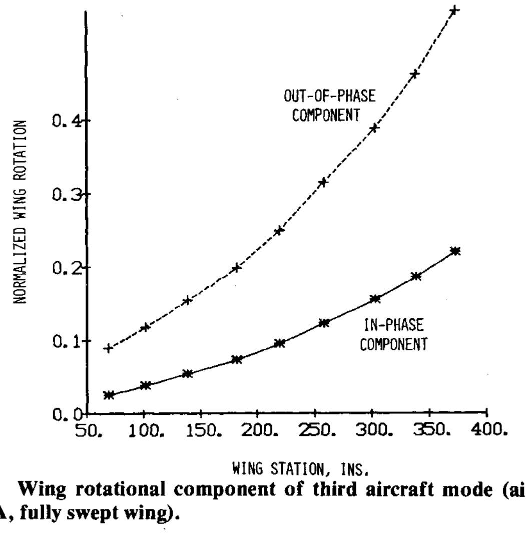

**Fig. 1 Wing rotational component of third aircraft mode (aircraft Type A, fully swept wing).**

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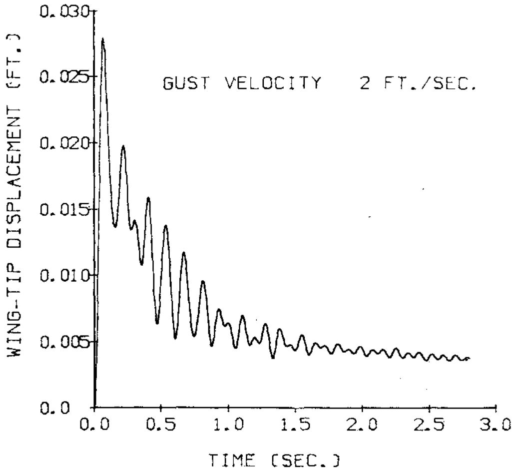

**Fig. 2 Type C response to sharp-edged gust.**

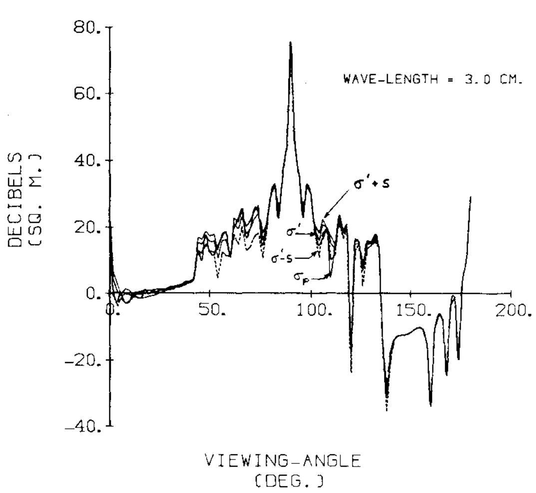

**Fig. 3 Static radar, scattering cross section.**

2) $\sigma'$, the static RCS by random phase where the different $\beta_j$'s are assumed to be randomly distributed

$$\sigma' = \sum_{j=1}^{6} \sigma_j$$

3) $\sigma' \pm s$, the bounds for the static RCS by relative phase where the rms spread is given by

$$s^2 = \left(\sum_{j=1}^{6} \sigma_j\right)^2 - \sum_{j=1}^{6} (\sigma_j^2)$$

Figure 3 shows the calculated static RCS for a 3 cm wavelength. The viewing angle is in the vertical plane and varies from 0 deg (head-on) to 180 deg (tail-on). These results are typical.[4]

The scattering centers of the aircraft experience vertical motion in time similar to that of the mode of vibration of the aircraft, thus varying their relative phase angles and affecting the overall RCS. This can be accounted for by properly modifying the $\beta_j$. Details can be found in Ref. 6. The dynamic cross sections were obtained for the fundamental vibration mode of Type A, which has a wing-tip amplitude of 0.3 cm at 6 Hz. This dynamic RCS was calculated for various viewing angles over one complete vibration cycle. At a 45 deg viewing angle and 3 cm wavelength (Fig. 4) the total deviation in the RCS is about 8 dB. This modulation appears as a superharmonic of the vibration frequency. Such low-frequency variations in the dynamic RCS have been observed.[5] At most viewing angles the deviations from the static RCS are larger for a 3 cm than for a 30 cm wavelength.

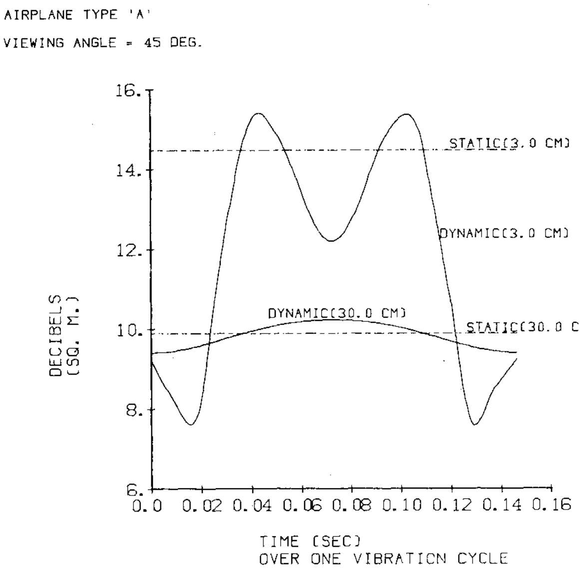

**Fig. 4 Dynamic radar, scattering cross section.**

## Conclusions

For a 3 cm wavelength, the dynamic RCS for an aircraft in flight shows a low-frequency modulation due to the structural vibration. Unfortunately, the elastic mode shapes and frequencies vary so greatly with airspeed and loading that identification is difficult. In addition, the amplitudes of vibration that could be routinely expected are below observable limits with current radar.

## Acknowledgment

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## References

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