

DESIGN AGAINST FATIGUE: VIBRATION OF STRUCTURES UNDER ACOUSTIC OR AERODYNAMIC EXCITATION

1. INTRODUCTION

This Data Item gives general guidance on the design of structures to avoid acoustically or similarly induced fatigue failures. The main consideration is for aerospace structures where a high strength-to-weight, and/or stiffness-to-weight, ratio is a prime aim. Components designed to overall static and dynamic conditions can still be susceptible to fatigue from fluctuating pressure loading. Often only local areas of the structure will be affected. Guidance is also given on the design of systems and equipment support structure and associated fittings.

The term acoustic fatigue implies the structural fatigue produced by the predominantly resonant response of structural components to radiated sound fields from, for example, jet and rocket engines. However a number of other excitation sources produce similar structural response phenomena, for example, fluctuating pressures in attached and separated boundary layers. Usually the basic parameters describing the structural surface dynamic loading are similar to those arising from a radiating sound environment. In order to assess the likelihood of acoustic fatigue in a structural region and to put the particular problem into perspective, some knowledge of probable sources of excitation and their characteristics is required. A review of acoustic and aerodynamic excitation sources is provided in Section 2. All of these sources have the potential to cause acoustic fatigue damage.

Section 3 gives information on the typical response behaviour of stiffened skin, box and cylindrical structures. Section 4 reviews a variety of structural configurations that may be used in a noise environment and the means of designing or modifying these configurations to resist acoustic fatigue at increasing excitation levels. Reference is given to relevant Data Items that may aid the choice of dimensions for the chosen structural configuration. The emphasis is on the design of the stiffened skin or shell of a component, but the design of the internal stiffening structure, such as ribs and frames, will also need to be considered. Here it may be necessary to consider the response of a box or cylindrical structure, for example the coupled response of skin panels with internal ribs and/or spars as described in Section 3.

Section 4 also provides some guidelines on good detail design for the structure. Features that give problems in fatigue under normal loading will often still be important under noise excitation; however, the nature of the resonant structural vibration and the associated response modes in the latter case will produce additional locations for potential damage. These potential damage locations have been indicated on some of the diagrams. Although the fluctuating stresses generated under noise excitation are normally very much lower than those occurring under the overall component loading, as used for conventional fatigue assessment, the influence of built-in or residual manufacturing and forming stresses may still be very important. Damage can be generated in regions where these retained stresses occur that may not have been previously considered areas for concern under the overall component loading. Reference should also be made to Item No. 74037 which outlines the procedure used to predict acoustic fatigue failures.

Section 5 provides information for assessing the design of systems and equipment support structure in a high noise level environment. These items will be mounted on the main structure and their excitation will usually be dominated by structure-borne mechanical vibration rather than direct acoustic excitation. In most situations it is the good detail design of the mounting that will ensure the required service life. A variety of examples is presented.

2. SOURCES OF EXCITATION

The primary sources of structural excitation are due to acoustic and aerodynamic generation although structurally transmitted vibration may have an additional influence. The characteristics of these sources, which are usually sufficient to define the excitation for the purpose of evaluating the response of the structure, are:

- (i) the variation of the sound or aerodynamic pressure levels over the structural surface,
- (ii) the associated variation of pressure with frequency,
- and (iii) the spatial correlation of the pressures.

Explanation of the implications of (i), (ii) and (iii) is given in Item No. 74037.

The sources of excitation that may need to be considered for aerospace structures are given below.

Source	Description	Characteristics
Efflux Noise		
Jet noise	The maximum levels of structural response due to jet noise usually occur with the aircraft stationary and engines running at maximum (take-off) power. Aircraft forward speed will generally cause the excitation levels to decrease although certain manoeuvres may cause an increase over some regions depending on the overall aircraft configuration.	Broad Band. Usually short term. Directional properties may be modified by reflections due to aircraft structure and ground.
Reference Item No. 72002	High levels may be experienced due to the operation of engine thrust reversers during landing.	Broad band. Short term.
	Jet flow may also be used to augment the lift of trailing-edge devices (jet-blown flaps) and will include thermal and direct flow impingement effects.	Broad band. Short term.
	High by-pass ratio powerplants (fan engines) are likely to have much lower jet exhaust velocities and produce lower noise levels.	Broad band. Short term.
Shock cell noise	In flight, with certain nozzle configurations and super-critical jet pressure ratios, a phenomenon known as shock cell noise or jet screech may excite structural vibrations. Its importance will depend on the aircraft configuration.	High intensity narrow band, directional. Probably long term, in flight.
Rocket noise	This will occur on launcher structures during the lift-off phase and is particularly important for reusable structure such as the Space Shuttle and may also be structurally transmitted to excite the payloads (see Additional Excitation Sources).	Broad band. Short term.
	Noise from missile launches will have a cumulative effect on adjacent structure.	Broad band. Short term (multiple).

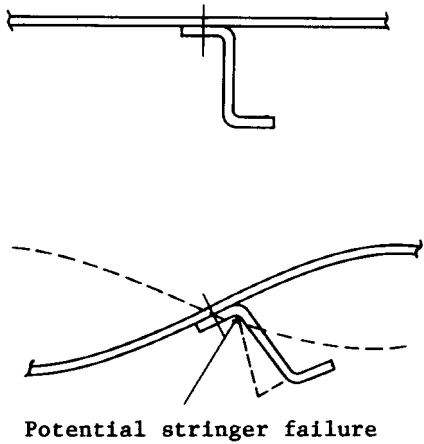
Source	Description	Characteristics
Spillage and exhausts	Noise affecting local structure can be generated by spillage or bleeds from intakes, exhaust from powerplant system bleeds and from auxiliary power units (APU), in many cases also being associated with high local temperature.	Generally broad band, some sources narrow band. Duration will depend on system operation.
Turbulent Flow - Small Disturbances		
Boundary layer turbulence	This can be a source of fatigue loading although, for a given pressure level, its effect is less than jet noise due to its correlation characteristics. However, high excitation levels can be generated by sharp profile changes in a high velocity flow, such as may occur on supersonic aircraft, launch vehicles and missiles.	Broad band. Possibly long term.
Reference Item No. 75021		
Leading-edge vortices	These can be a source of fatigue loading occurring on aircraft with sharply swept leading edges. They are only likely to be of importance when the wing is at high angles of incidence or in prolonged sideslip.	
Engine intake ducts	High noise levels may be generated in certain designs of intake, especially for supersonic aircraft where devices are used to control the aerodynamic flow. High levels may be associated with certain operating conditions.	Broad and/or narrow band. Possibly long term.
Flow over cavities	High noise levels can be generated by airflow over cavities such as undercarriage and weapons bays when in the open configuration. This noise source is usually amplified by cavity resonance effects.	Broad band with high intensity tonal content.
Turbulent Flow - Large Disturbances		
Buffet	The breaking away of aerodynamic flow can cause large fluctuations of surface pressure on flight surfaces and/or fuselage structure, generally termed buffet. It will be most likely to occur towards the extremes of the envelope of operating conditions.	Characteristics will depend on structural geometries and operational conditions.
Buffet due to aerodynamic control surfaces	The operation of airbrakes and spoilers (lift dumpers) will cause pressure fluctuations to act on the structure behind them. The surfaces themselves may also be subjected to fluctuating pressures. High lift devices such as leading-edge slats and trailing-edge flaps may generate fluctuating pressure loading on local structure, as for airbrakes.	Broad band, frequency content usually dependent on surface shape, displacement, velocity, etc.

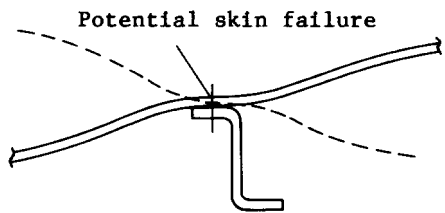
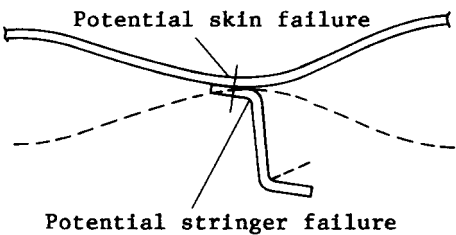
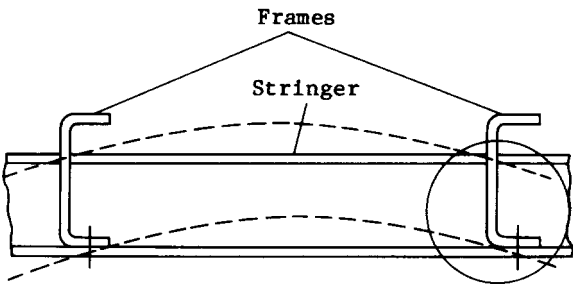
Source	Description	Characteristics
Wing stores	Turbulence behind blunt ended wing stores can affect local structure, depending on the store shape and the flow velocities. <u>Note.</u> Structural items causing a large disturbance in the airflow may produce high levels of mechanical vibration affecting their attachments or operating systems.	
Direct Powerplant Sources		
Powerplant bay	Noise and transmitted mechanical vibration will be present in powerplant and APU bays and may also be present close to gearboxes. This excitation may affect local structure, thermal insulation, flame shields and powerplant systems installations.	Generally broad band, present while powerplants or APU are operating.
Jet and rocket nozzles	Structure, thermal insulation and systems installations will be subjected to higher noise levels than for powerplant bays and will include a more severe thermal environment. Nozzle, jet pipe and thrust reverser structure will itself be liable to acoustic fatigue.	Broad band, present whilst engine operating.
Propeller and Fan Noise		
Propellers Reference Item No. 95029	Propellers can produce high sound pressure levels affecting structure approximately in line with the propeller disc.	Discrete tones, long term.
Fan or compressor noise Reference Item No. 74033	The engine compressor (fan) blades, consisting of rotors and stators, will generate high level tones that will affect structure near blade tips and also propagate both up- and downstream affecting intake and exhaust duct structure. Tuned absorbers incorporated in the duct structure to reduce the externally propagated noise will also be subjected to fatigue.	Discrete tones, usually long term but may be associated with particular operational engine speeds. Both high frequency tones and low frequency ("buzz-saw") tones may be generated.
Multi-bladed propellers and unducted fans	The multi-bladed high speed propellers or the use of unducted fans will generate a more severe acoustic excitation than the basic propeller. Structure approximately in line with the propeller or fan disc will be affected.	Discrete tones, high level, low frequency. Long term.
Additional Excitation Sources		
De-icing ducts	De-icing ducts may be a source of noise and mechanical vibration whilst in use.	
Hydraulic pumps	Mechanically driven hydraulic pumps can be a source of pressure pulsing that is transmitted by the hydraulic fluid and can cause resonant excitation in the pipe lines.	Discrete pulses linked to drive speed.

Source	Description	Characteristics
Gunfire induced vibration	The blast produced will affect the armament bay and local aircraft structure.	High level, repetitive transient.
Sound source for spacecraft acceptance or qualification test	The sound produced in a reverberant chamber for the testing of spacecraft components. This is intended to simulate the transmitted noise produced in the launch vehicle payload bay during lift-off and ascent.	Diffuse broad band noise field, short term.

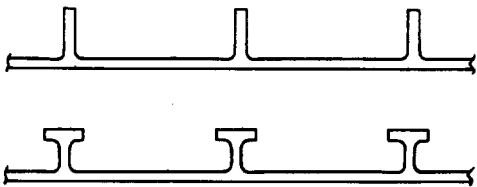
3. MODES OF STRUCTURAL RESPONSE AND ASSOCIATED TYPES OF FAILURE

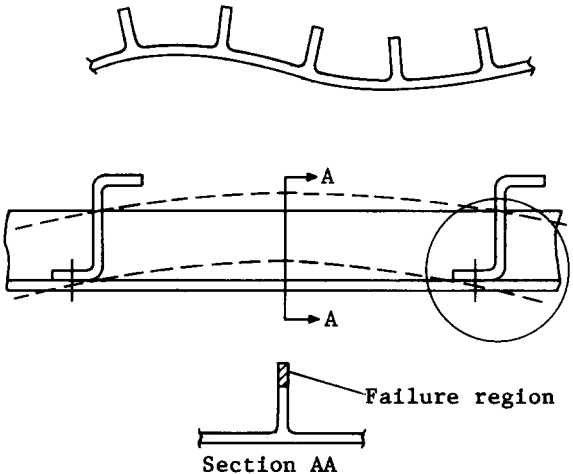
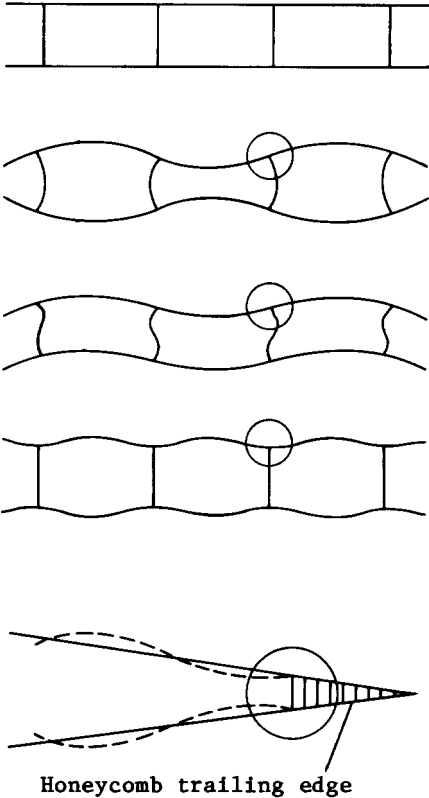
A knowledge of the likely behaviour of a structure under fluctuating pressure loading will aid the identification of potential locations for the initiation of damage. This may indicate where a particular structural configuration can be improved. For some components it will be necessary to consider the possibility of coupled response modes affecting the whole, or a large section, of that component. The table below gives some general examples of structural response modes and potential failure locations with reference to relevant Data Items used to evaluate natural frequencies. Section 4 presents current design practices that are used to improve various configurations and also provides examples of alternative constructions. The present prediction technique is based on a single predominant mode response and it is usually a lower order mode that has the largest structural displacements producing the highest stresses. However the predominant structural response is also dependent on the frequency content of the excitation.

Feature	Response	Potential Damage
Conventional Fabricated Structure Item No. 72003 provides a means of evaluating panel natural frequencies Open Section Stringer – Torsion Mode	 Potential stringer failure	Stringer failure more probable

Feature	Response	Potential Damage
– Torsion Mode (Torsionally-stiff stringer)	 Potential skin failure	Skin failure more probable.
– Bending Mode	 Potential skin failure Potential stringer failure	Potentially more damaging than torsion mode but effect will depend on relative displacements and stresses due to excitation spectrum.
Stringer End Fixing (Bending and torsion modes)	 Frames Stringer	Fixing or cleating of stringers at frame is a source of failure (see Section 4.2).

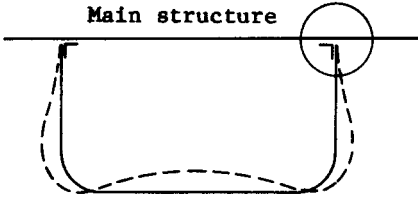
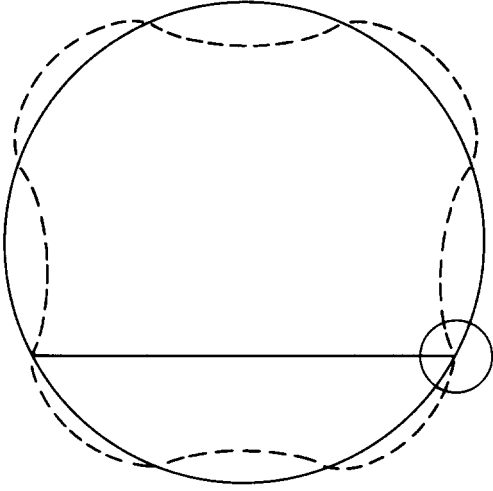
General Note: All of the above response modes can produce fastener failures (particularly for rivets) although material failure is more probable.

Feature	Response	Potential Damage
Integrally Stiffened Skins Item No. 73013 provides a means of evaluating panel natural frequencies.	 Typical integrally stiffened skin configurations are shown. The type of stringer normally used is often more flexible in torsion and bending when compared to fabricated structure and damping will be lower than for a built-up structure.	

Feature	Response	Potential Damage
Different mode distribution from fabricated structure, stringer may not be at nodal points.		Fixing or cleating of stringers at frame is a source of failure. High stresses can also be generated at mid-stringer and/or frame locations leading to stringer cracking.
Box Structures Item No. 74025 provides a means of evaluating natural frequencies. Possible Response Modes. With many structures coupled modes will also exist in the third dimension. Tapered Section Box structures (control surface)		Skin/rib junctions may be critical, failures are possible on internal members. The stiffness of the internal member will considerably influence the skin response. Attachment of a honeycomb trailing edge may present a critical location.

General Note:

Due to this coupled mode response, when the excitation is incident on one face of a box structure, the other skin surface can still experience relatively high response levels. Some structures may experience excitation on both faces and consequently produce coupled modes with very high response levels. Factors for estimating the effect on stress evaluation are given in Item No. 67028 and should apply to the basic panel, rib and spar structure. However the structural junctions between these features may require special consideration.

Feature	Response	Potential Damage
Fairing Structures (Jack or flap track cover)		Fairing attachment: either attachment bracket or local fairing structure.
Cylindrical Shells (Excitation over a large surface area) Item No. 78004 provides a means of evaluating natural frequencies for unstiffened cylinders and Item No. 80040 for stiffened cylinders, both thin-walled. Item No. 81018 extends the unstiffened evaluations to thick-walled cylinders.	 The lowest frequency mode* for overall ring response will consist of several circumferential half-waves. Nodal locations may be influenced by structural features such as engine mountings, nacelle attachments or internal beams.	The panel response will be influenced by the cylinder ring modes, although the potential damage locations will be as described for fabricated or machined structure. Additionally potential damage locations will occur where internal members are attached to the cylinder shell.
*For footnote see end of the table		

Feature	Response	Potential Damage
Composite Structures Laminated Plates Item No. 83036 provides a means of evaluating natural frequencies for laminated plates. Sandwich Panels with Laminated Face Plates Item No. 85037 provides a means of evaluating natural frequencies for sandwich panels having laminated faceplates.	The responses modes for composite structural configurations will be dependent on the degree of anisotropy and will not generally be the same as those for similar metallic structures.	The types of damage incurred by these composite structures will differ from those in metallic structures, although the failure locations will still be influenced by the predominant structural mode shape.

* This applies to a thin cylindrical shell having a relatively large radius to thickness ratio ($R/t > 20$) such as usually occurs in aerospace structures. See Item No. 81018 for the modal response of a thick-walled cylinder.

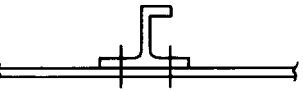
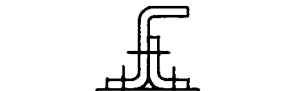
4. DESIGN AGAINST ACOUSTIC FATIGUE

This Section gives information on structural configurations that may be used in a noise environment and the means of designing, or modifying, these configurations to resist acoustic fatigue.

The first part of this Section gives a review of current practice used for basic stiffened skin design and for internal support structure. Most of the configurations can be supported by calculations and reference is given to appropriate Data Items which may be used to estimate the structural dimensions required to resist a selected excitation level and meet the life requirement. Item No. 74037 outlines the procedure used to predict acoustic fatigue life.

The second part of the Section gives a selection of ways to improve life by good detail design. The features presented do not currently allow life assessment by calculation; however, they have all been proven in practice. The examples given in this Section are based on actual case studies.

4.1 Good Current Practice in Stiffened Skin Design

Description of Feature	Layout	Design Details
METALLIC STRUCTURES Conventional Fabricated Structures Most skin failures will be initiated from fastener holes and use of the following techniques will improve life. (i) Increase basic skin thickness. (ii) Increase skin thickness local to fastener. – provides effective reduction in panel width. – provides skin thickness for countersunk fasteners. (iii) Use double-row of fasteners. – provides effective reduction in panel width. – skin bending occurs only along one of each fastener row. (iv) Use backing angle. – stiffens frame or stringer web. – reduces potential failures at heel radius.	 Basic scheme  Chemically etched skin  Alternative: bonded doubler  Extruded section stringer shown  Backing angle shown in combination with local reinforcing	Item No. 72005 provides a means of estimating stress for stiffened skin panels. Item No. 67029 provides a means of estimating the effect of reinforcement on skin stresses.