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A Brief Review of Unsteady Aerodynamic and Aeroelastic Phenomena of a Fan Installation.

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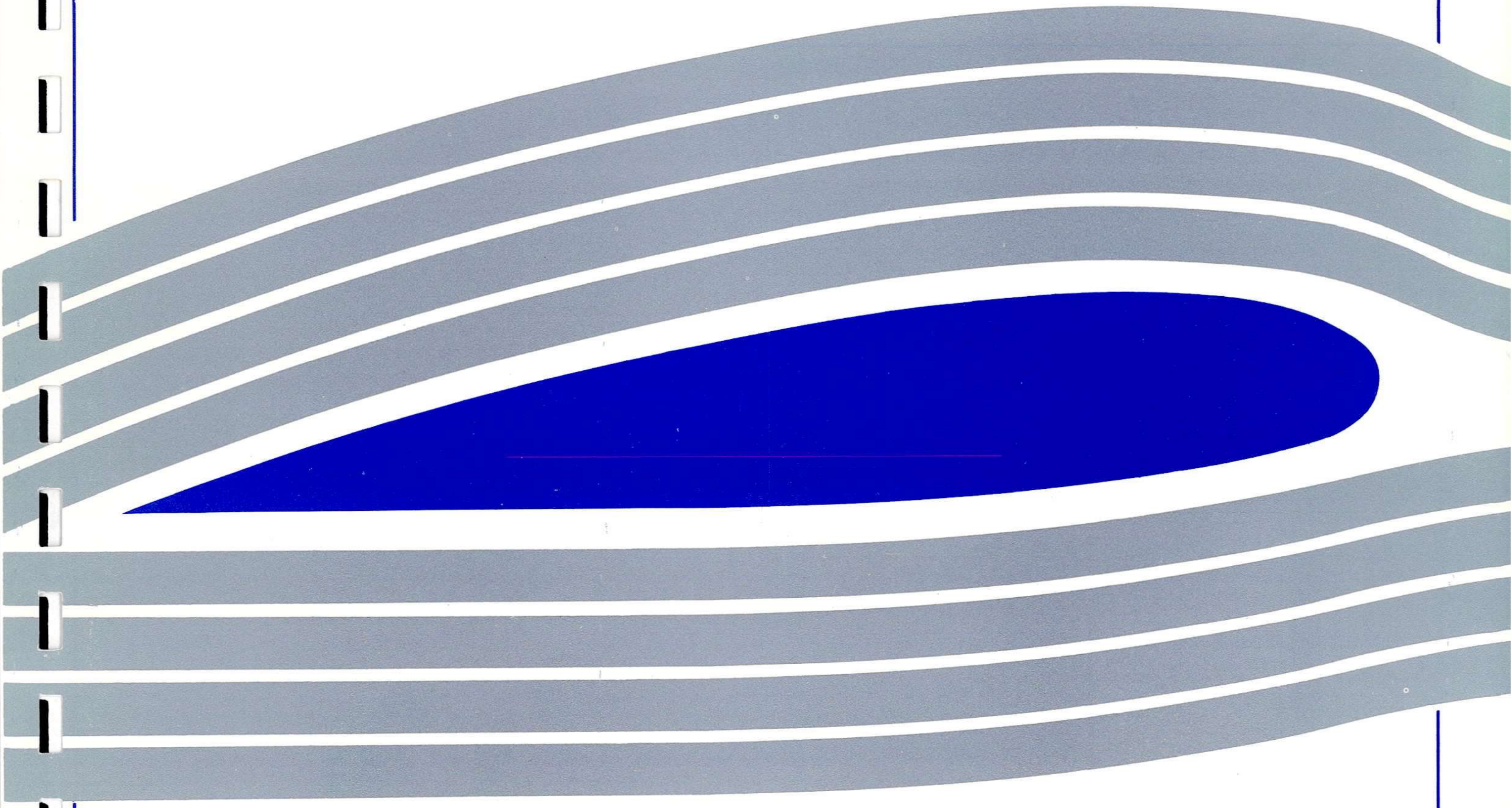

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A Brief Review of Unsteady Aerodynamic and Aeroelastic Phenomena of a Fan Installation.

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on behalf of

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G.U. Aero Report No. 9719
October 1997.

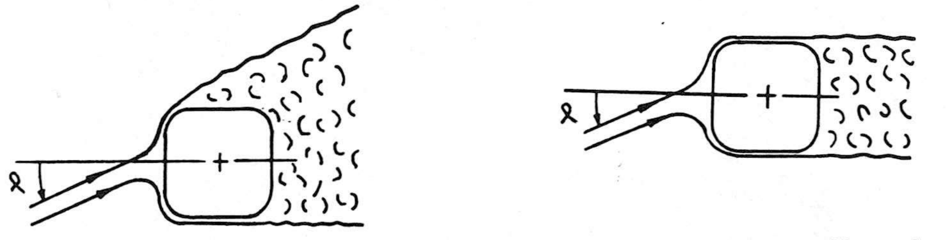
Summary

This report contains a brief review of the unsteady aerodynamic and aeroelastic phenomena of relevance to the operation of the Inco fan installation. The review addresses issues associated with unsteady inlet flow phenomena due to an upstream vortical wake and the aeroelastic flutter characteristics of the rotor assembly.

Based on the available information on inlet flow and blade structural dynamic characteristics a number of conclusions are made. Firstly the vortical wake will be three dimensional in nature, although the von Karman vortices generated from the motor housing will predominate. These have the potential to induce vibration in the fan blading, and should be investigated further. Secondly, it is recommended that the potential for stall flutter and single mode bending-torsion flutter be further investigated.

1. Vortex Shedding from Bluff Bodies.

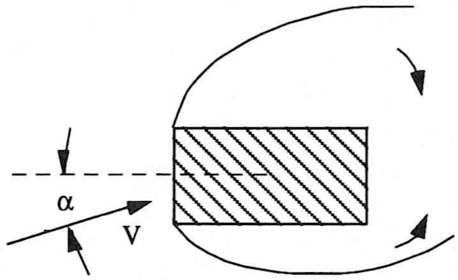
The presence of a body in an air stream causes the air to divert around the body. Unless a sufficiently streamlined profile is presented to the oncoming stream the flow will detach, or separate, from the body surface. In general, for a stationary body in incompressible flow, the locations of the separation points on the surface are dependent on flow incidence and Reynolds number. However, if the body surface is characterised by sharp edges then the separation points are generally located at one or more of these edges and are essentially independent of Reynolds number. Fig. 1.1 illustrates these ideas in the case of two dimensional flow, that is where conditions pertaining to infinite aspect ratio are assumed.



Subcritical Reynolds number

Supercritical Reynolds number

(a) bluff body - smooth surface, Re dependency



(b) bluff body - sharp edges

Fig. 1.1. Flow conditions around bodies in 2-D flow

The wake of a bluff body results in velocity fluctuations which are much more coherent and of greater magnitude than natural flow turbulence. The fluctuations are caused by the alternate shedding of vortices of opposite sign from the sides of the body, as indicated in Fig. 1.2.

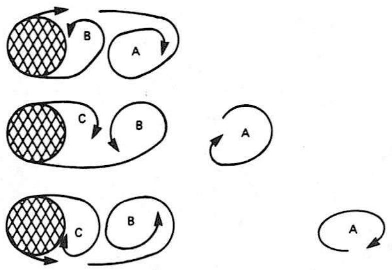


Fig. 1.2. Vortex shedding from a body in 2-D flow

The so called *von Karman* vortices are defined by vortex filaments which extend (infinitely in theory) out of the flow plane. These are transported downstream in the wake, forming a *vortex street*. The frequency of vortex shedding is characterised by the non-dimensional *Strouhal* number $S=\frac{fb}{V}$, where f, b and V are the shedding frequency of complementary vortex pairs, the characteristic body dimension (usually cross-stream) and the flow speed respectively.

Cyclic cross-stream forcing occurs on the generating body at frequency f, which generally varies linearly with V for sharp edged bodies. In addition, along-stream forcing occurs at frequency $2f$, as this mechanism is related to the cyclic drag which is driven by the shedding of individual vortices. If the body is free to vibrate then the response is maximised when $f = N$, the fundamental natural frequency of the body. In this case vortex "lock-in" tends to occur in which the frequency of shedding is tied into the oscillation frequency of the body over a limited speed range, as illustrated in Fig. 1.3.

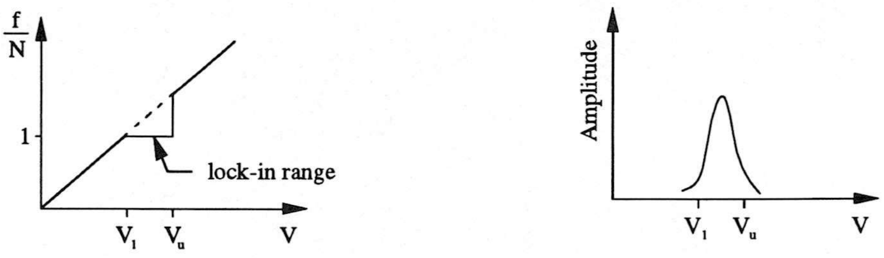


Fig. 1.3. Vortex excitation of a bluff flexible cylinder

A body which is immersed in the vortex wake of another will also experience cyclic forcing, with consequences similar to those described above should the forcing and natural frequencies coincide. Significant excitation can be induced on a body located as far as $8b$ downstream. Further downstream the structure of the vortices becomes more chaotic as momentum is transferred from the coherent vortex structures to lower strength, broader band turbulent eddies.

The wake of a body in two dimensional flow does not remain two dimensional due to distortion and turbulent dissipation of the vortex filaments as they progress downstream. However the flow around a low aspect ratio body produces a highly three dimensional wake from the body itself. Fig. 1.4 illustrates the basic features of the flow about a rectangular block, from which the additional vortex structures can be identified.

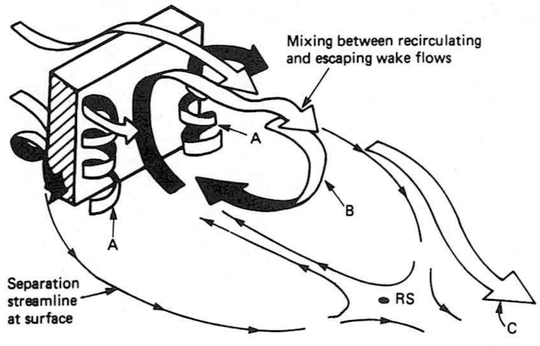


Fig. 1.4. 3-D vortex shedding from a rectangular block

Inco Fan Motor Housing

Of particular concern is the location of the motor housing upstream of the fan inlet. The basic geometry of the housing is illustrated in Fig. 1.5, which also indicates the onset flow direction.

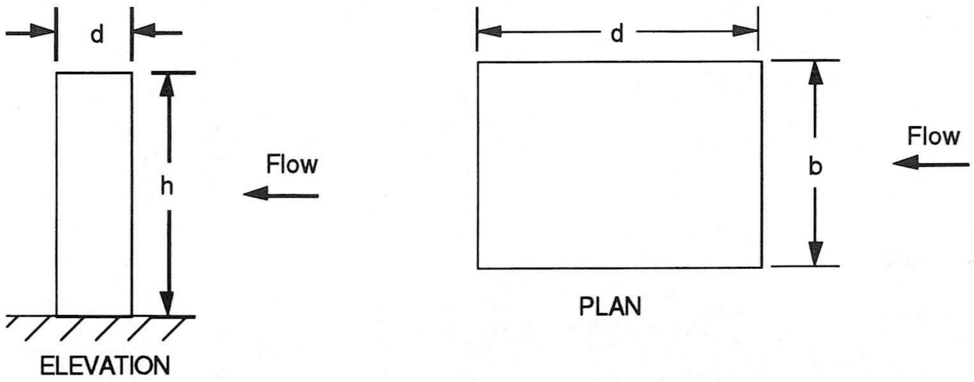


Fig. 1.5. Geometry of motor housing

The dimensions h, d and b are 6.325m, 1.956m and 1.422m respectively, and the lee face of the box is located 5.283m from the fan inlet. The ratio h/b is 4.45, which should be doubled because of the ground plane, resulting in a value of aspect ratio of 8.9. At such values three dimensional shedding patterns should still be in evidence but the predominant shedding would be of the von Karman type in the plane of the cross-section illustrated in the plan of Fig. 1.5. The cross-sectional aspect ratio d/b is 1.38. Fig. 1.6 illustrates the Strouhal number variation with aspect ratio for rectangular sections. For the given aspect ratio the Strouhal number is 0.11.

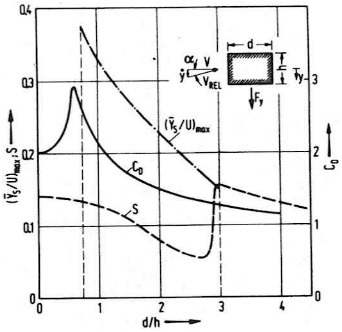


Fig. 1.6. Variation in Strouhal number with section aspect ratio

The predicted frequency of the von Karman shedding can be calculated from the Strouhal formula:

$$f = \frac{SV}{b} = 0.077V$$

where V is the onset flow speed at the housing. Note that the shedding of individual vortices is predicted to occur at twice this value ($0.154V$).

The distance of the fan inlet from the lee face of the box is $^{5.283}/_{1.422}$ or 3.72 body dimensions, which can be considered as close proximity. This means that the shed vorticity, notwithstanding the three dimensional interactions referred to above, should possess a strongly coherent component at the fan inlet. The inlet contraction should aid the process of vortex dissipation into smaller eddies, although the duct length between fan inlet and rotor is very short for this process to advance significantly. The remainining coherent structures have the potential to induce vibration in the fan blading, which may be examined in the light of the above information.

2. Flutter Phenomena in Axial-Flow Fans and Compressors

Flutter is a generic term used to describe a variety of self-excited dynamic aeroelastic instabilities. In general, axial-flow fans and compressors exhibit several distinct forms of flutter including stall flutter, choke flutter, and unstalled (or potential flow) flutter. For many years, stall flutter and choke flutter were considered the only possible types of flutter. However, current thinking is that unstalled flutter of cascades is also significant. This section describes the flutter phenomena appropriate to axial-flow fans and compressors operating in essentially subsonic flow regimes.

2.1 Stall Flutter

Stall flutter in rotating blades is manifest by the appearance of coherent unsteady flow separation from the suction surface of the blades in which the blades vibrate sporadically at, or near, their natural frequency. There is no apparent correlation between the motions of adjacent blades, and the amplitudes of the vibrations change with time in an apparently random manner. This behaviour is distinct from vibration attributable to resonance with propagating stall which is essentially a flow instability phenomenon.

Stall flutter is usually observed in the first torsional vibration mode. Empirical evidence suggests that the most important parameters governing stall flutter are the incidence and the reduced velocity $V/b\omega$ (the inverse of reduced frequency) at some characteristic radius of the blade such as 75%. Here, V is the flow speed, b is a characteristic dimension (usually the blade semi-chord), and ω is a reference blade frequency (usually the first torsional natural frequency).

Figure 2.1 shows a typical stall flutter boundary in the reduced velocity ~ incidence parameter space.

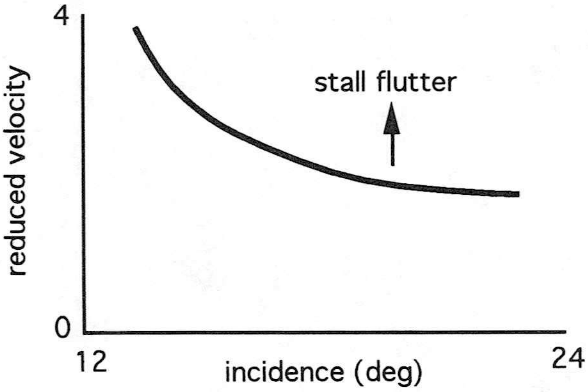


Fig. 2.1

2.2 Unstalled Flutter

The unstalled flutter instability encountered in rotor blade assemblies of axial-flow fans and compressors typically takes the form of a cascade induced single mode blade-to-blade interaction flutter where both bending and torsion components in the blade vibration mode, and their relative size, play an important role. This is in contrast to the classical aeroelastic bending/torsion coalescence flutter of an isolated wing in which two or more vibration modes are involved.

In general, the blade-to-blade flutter mode is characterized by a travelling wave pattern of the blade row in which all blades oscillate harmonically with the same

mode shape and frequency but with a certain (constant) phase shift relative to each other. The origin of the interblade phase difference is the motion-induced unsteady aerodynamic forces which depend on individual blade motion history and the motion history of neighbouring blades. For N blades there are N possible interblade phase angles $\theta_n = 2\pi n/N$, $n = 0, 1, \ldots, N-1$.

While the assumption that the flutter mode shape coincides with a (single) vibration mode of the rotor is generally unreliable, particularly in the practical range of reduced frequencies, the error in this assumption decreases with increasing kinematic coupling in bending and torsion. Moreover, as the mass ratio of a solid metallic fan or compressor blade is generally large, both the flutter frequency and the corresponding flutter mode remain relatively unaffected by the aerodynamic loading. In practice, the flutter mode shape is usually (but not necessarily) associated with the lowest natural frequency blade vibration mode. However, within the practical range of design parameters and kinematic coupling, experimental evidence suggests that both torsional and bending branches can exhibit instability.

Figure 2.2 illustrates the essentially single mode flutter characteristics of typical blade assembly. The schematic is derived from a two-mode flutter analysis based on the first bending and first torsional modes. The relative frequency is defined as ω/ω_T and the reduced velocity as $V/b\omega_T$. Here, the critical mode is associated with first torsional vibration mode.

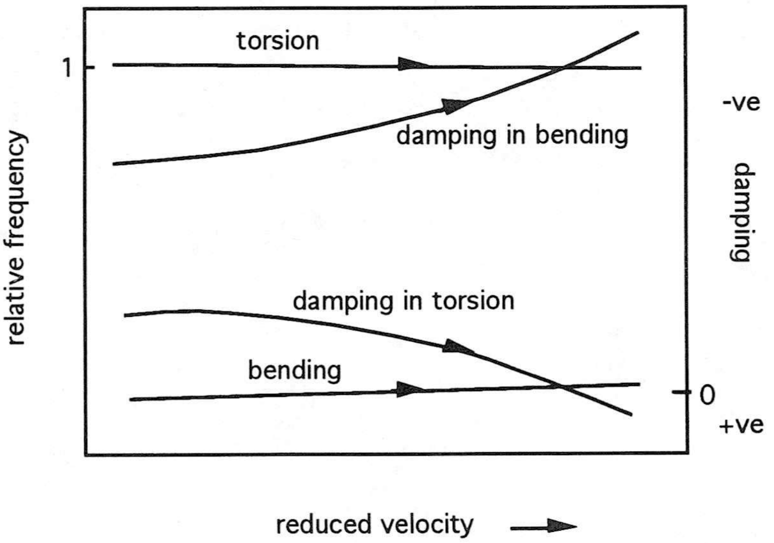


Fig. 2.2

Assessment of the aeroelastic stability characteristics of a blade assembly is generally achieved through calculation of the neutral stability boundaries for a range of design and operating parameters (for example, mass ratio, structural damping, kinematic coupling, etc.). For preliminary design purposes, the blade assembly is assumed to be structurally tuned and the inlet flow velocity is assumed the same for all blades. For a tuned rotor subject to a single mode flutter, the concept of constant interblade phase angle implies that the travelling wave modes associated with θ_n are the aeroelastic (flutter) eigenmodes.

At the critical stability condition, the motion is sinusoidal and the interblade phase angle is constant. As a result, evaluation of the unsteady aerodynamic forces is feasible. In general, the unsteady aerodynamic forces depend on reduced frequency

and interblade phase angle. Flutter occurs at those values of reduced frequency and assigned phase angle θ_n satisfying the flutter eigenvalue problem. From these values, the critical inlet velocity V_F can be determined. Among all solutions V_F for the given discrete values θ_n, the minimum value of V_F is the physically correct critical flutter velocity.

The qualitative effects of variation of the primary design and operating parameters on the flutter characteristics of a typical blade assembly can be ascertained from the resulting stability diagrams.

Mass Ratio and Structural Damping
In the absence of structural damping, the stability boundary is independent of mass ratio. However, if structural damping is present a rotor blade with a large mass ratio (such as a solid metallic blade) will be more stable (that is, possess a higher critical flutter speed) than a blade with a small mass ratio. For non-zero structural damping, the mass ratio determines the magnitude of the destabilizing aerodynamic effect which can be tolerated before the system becomes unstable. In general, the stabilizing effect of structural damping is more pronounced in the case of bending flutter than in torsion flutter. Also, the range of interblade phase angle at which flutter occurs is constricted by the stabilizing effect of structural damping.

Kinematic Coupling in Bending and Torsion
Kinematic coupling in bending and torsion plays a fundamental role in the aeroelastic coupling amongst oscillating blades. Important sources of kinematic coupling include blade pre-twist, centrifugal forces, and any offset between the blade inertial axis and elastic axis.

Figure 2.3 illustrates the influence of kinematic bending/torsion coupling on the critical flutter reduced velocity, $V_F/b\omega_T$, under variation of the bending/torsion vibration mode frequency ratio $\gamma_\omega = \omega_B/\omega_T$ (in this example, the blade elastic axis is located at the mid-chord). In the vicinity of vibration mode frequency coincidence, $\gamma_\omega \cong 1$, the critical flutter velocity is dramatically reduced and is almost independent of kinematic coupling.

The frequency ratio for first bending/first torsion modes of fan blades typically is in the range 0.3-0.7. However, current technology fan blades have second bending and first torsional natural frequencies close together with frequency ratios in the range 0.8-1.2. It is possible, therefore, that interactions between second bending and first torsional modes may be potentially hazardous. In addition, for blades with low mass ratio, aerodynamic mode coupling could lead to classical coalescence flutter.

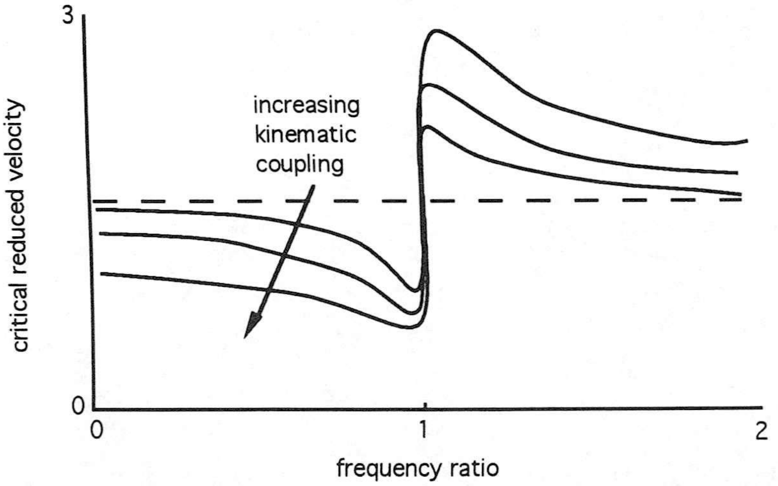


Fig. 2.3

3. Conclusions

Based on the brief assessment provided in sections 1 and 2, the following conclusions are made:

- The upstream flow into the fan will consist of a vortical wake generated from the motor housing. This wake will be three dimensional in nature but will consist predominantly of von Karman vortices in the plane of the cross-section. This unsteady flow has the potential to induce vibration in the fan blading and should be investigated further in association with the blading structural dynamic properties.

- An assessment of the propensity of the blade assembly to encounter stall flutter is required. In addition, the possibility of a potentially hazardous single mode unstalled flutter involving the second flap vibration mode and first torsional vibration mode requires further clarification due to the close proximity of the natural frequencies of these modes.