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VIBRATIONS: SESSION A: STRUCTURAL ANALYSIS AND DAMPING

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THE DAMPING OF STRUCTURAL VIBRATION BY SLIP IN JOINTS

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1. Introduction

Modern construction methods continue to encourage unwanted structural vibration because the trends to low mass and welded joints reduce the inherent damping. Special high damping alloys are available, although they tend to be expensive, as are laminated beams incorporating high damping layers - the latter are also temperature and frequency sensitive. However, in bolted structures, the total vibration energy dissipation is usually dominated by frictional damping in the joints; this mechanism therefore providing the greatest potential increase in structural damping.

Frictional damping mechanisms are presented followed by a description of certain surface preparations which can reduce the damaging effects of fretting corrosion. The energy losses that can be achieved by utilising frictional damping, and the effects on the transient and resonant response of structures are discussed. Linearised theoretical solutions to the equations of motion give acceptable results under macro-slip conditions.

2.1 Frictional Damping

When two dry surfaces are brought together, the points of contact - the asperities which are always present even on the finest machined surfaces - deform elastically and plastically until sufficient area is brought into effect to support the load: the degree of intimacy between the projecting parts of the two surfaces will vary from one case to another. Of the types of interaction that can occur if a cyclic tangential load is applied to a joint interface, the mechanisms to which energy dissipation can be attributed are;

a. A cyclic plastic deformation of the contacting asperities;
b. Micro slip of the joint interfaces;
c. Macro slip of the joint interfaces.

In joints with high normal interface pressures and relatively rough surfaces the plastic deformation mechanism is significant. Very many joints have to carry pressures of this magnitude to satisfy criteria such as high static stiffness. In some joints, all three mechanisms operate - the relative significance depending on the joint conditions. A low normal interface pressure would tend to increase the significance of the slip mechanisms, as would an improvement in the quality of the surfaces in contact. The damping capacity of a lap-joint subjected to partial interfacial slip has been shown to be a maximum when force transference is only by

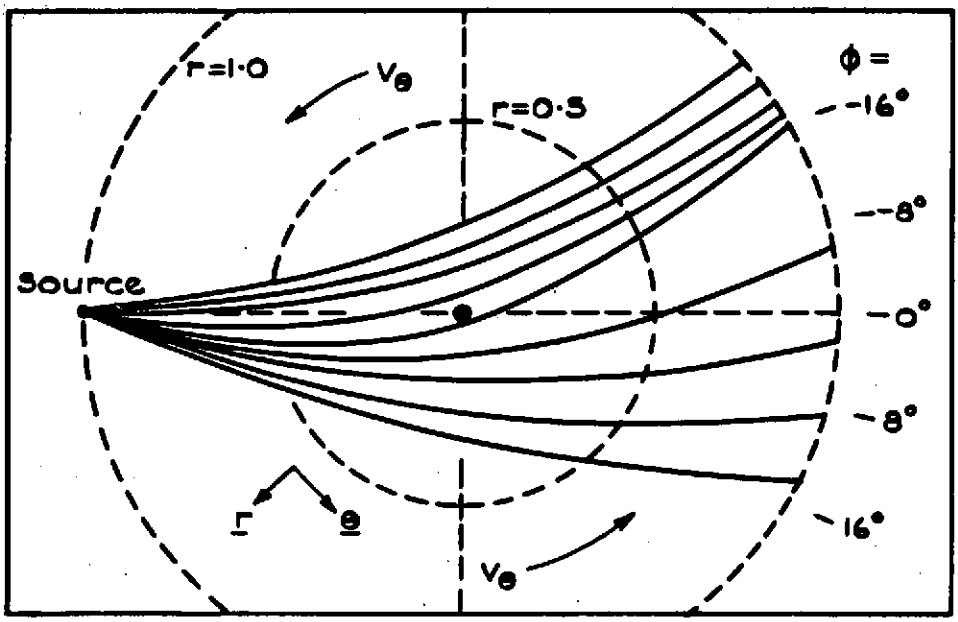

Fig.1 Ray paths through a rotating flow with constant azimuthal velocity

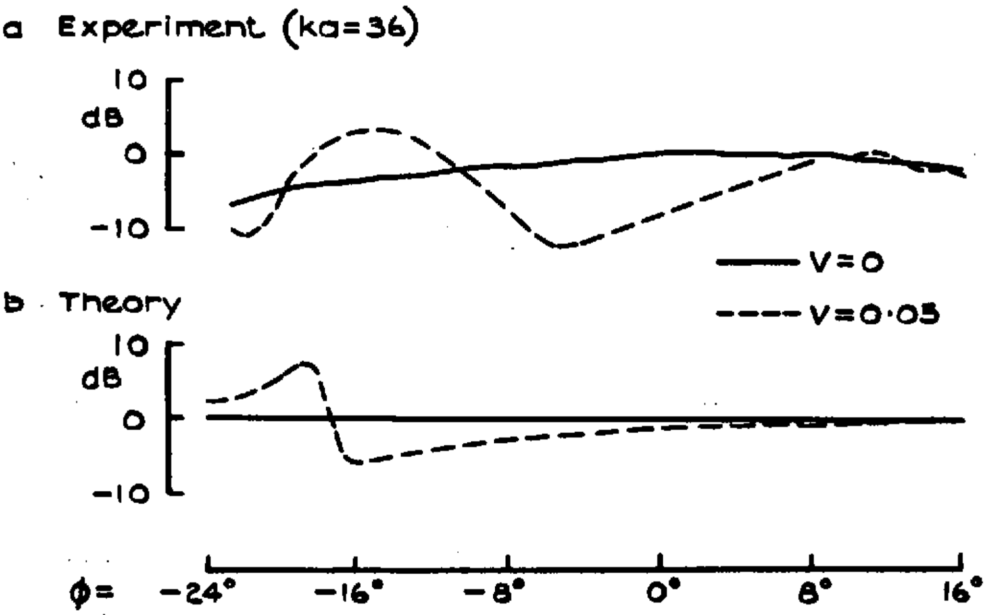

Fig.2 Measured and calculated sound intensity distribution

friction throughout the joint (1,2).

With the macro slip mechanism, the energy dissipation is proportional to the product of the interface shear force and the relative tangential motion. Thus under high pressure the slip is small and under low pressure the shear force is small: between these two extremes the product becomes a maximum. However, fretting corrosion can be instigated by relative interfacial slip in a joint. This is a particularly serious form of wear, encountered when two surfaces nominally at rest with respect to each other are subjected to slight vibrational slip.

2.2 Fretting Corrosion

The initiation of the fretting process consists of the breaking down of any natural protective film covering a surface by oscillatory motion so that metal or oxide is broken away at each oscillation. The metal so broken away then oxidises and, together with the oxide debris, may act as an abrasive causing serious damage. After fretting action has started the initial intermetallic contact is quickly broken and the surfaces become separated by a layer of finely divided oxide debris. Thus, although the initial wear action is similar in form to that which occurs between any two sliding surfaces, as soon as the oxide debris compact builds up, further wear must be due to the interaction of the oxide debris and the surfaces and not to the interaction of the surfaces themselves.

If fretting occurs on a large scale in a joint two major undesirable effects may occur:

a. The fretting may introduce serious corrosion damage within the joint and initiate cracks with ultimate fatigue failure.
b. The fretting action may allow the joint to drift from the pre-set damping condition or cause jamming of critical clearances.

Although fretting corrosion has been the main reason why frictional damping has been neglected as a useful source of structural damping, it may be preferable to the large resonant stress amplitudes which may occur if all the joints in a structure are rigidly fixed to prevent slipping. Fortunately, however, several methods are available for controlling fretting corrosion: they range from encouraging sliding to encouraging seizure.

2.3 Surface Preparation

When assessing the effect of surface preparations under conditions of fretting fatigue, their effect on the fatigue properties of the material to which they are applied must also be considered. A compressive surface stress generally improves the fatigue properties; a preparation which attacks the surface may provide stress concentrations. Failure to do so may bring results more deleterious than the fretting damage itself.

A method frequently used to promote seizure is to provide a layer of low elastic modulus or low yield strength so that relative motion is taken up within the layer. Sliding can be encouraged by using non-metallic coatings to provide a low coefficient of friction. However, such treatments are likely to be of limited use in structures. Greases tend to squeeze out from between the mating surfaces and resin bonded surface coatings or plastic skins have only moderate strength, so that asperities on the joint surfaces tend to break through the protective layer. Moreover, some of these coatings reduce the coefficient of friction and might therefore be unsuitable for certain types of joint.

Direct contact of the load bearing surfaces can be prevented by metal spraying the mating surfaces (3). Although fretting occurs the cracks formed propagate only within the sprayed metal. Similar improvements in fretting fatigue behaviour can be achieved by shot peering or sand blasting the surfaces of the joints, since the cracks produced by fretting are unable to propagate through the sub-surface layer of compressive stresses induced.

Results obtained (4) by applying the ICI Sulfinuz coating to 0.16%C steel show a great improvement (a five fold increase in the number of cycles required to induce a fatigue crack) in fretting resistance. Both the coefficient of friction and the fatigue strength are increased.

Since the maximum energy dissipated by interfacial slip in a joint is independent of the coefficient of friction (5), the joint interfaces can be chosen to minimise the damaging effects of fretting corrosion. Results from some tests done on sand blasted joint surfaces show that blasting which is severe enough to increase the surface hardness and roughness reduces the fretting corrosion without materially affecting the maximum energy dissipated: the joint clamping load for this conditions is altered however due to changes in the coefficient of friction brought about by the surface preparation.

2.4 Humidity

Little is known about the effect of humidity on joints subjected to interfacial slip. For outdoor structures such as transmission line towers this effect requires investigation. Condensed moisture may lubricate the debris and tend to decrease wear but conversely chemical corrosion may increase the total damage of steel.

3. Damping Effects

Energy losses capable of providing a highly beneficial reduction in resonant stresses can be achieved by frictional damping (5,6). To achieve maximum energy loss joints must be designed so that a particular value of clamping load at the interface is maintained: for maximum energy loss a clamping load is required which is one half of the value required to prohibit gross slip. The amplitude of slip under these conditions is one half of the amplitude for zero clamping load: this indicates a simple practical method of adjusting a joint to provide maximum energy conditions. However, these results were obtained using low interface pressures (less than 100 $lbf/in^2 \sim 700\ kN/m^2$) for maximum energy dissipation: pressures in this range are unlikely to be found in many structural joints but could be used in a friction damper.

The effect of frictional damping on the transient bending vibrations of beams has also received some attention: it has been demonstrated (7) that for a given amplitude there is a clamping load to give the fastest decay. Applying frictional damping to the unsupported end of a cantilever can produce a wide range of responses to an impulse dependent on the clamping load. Zero load gives damping dependent only on the cantilever material, a condition also achieved by a very large clamping load when the beam responds (fundamentally) at a higher frequency. A clamping load between these extremes introduces frictional damping with a consequent reduction in the decay time which can be optimised.

This facility for changing beam frequencies by frictional damping has been the subject of work (8) aimed at minimising structural responses to forced vibration rather than maximising the energy dissipated in the joints. The structure considered was an elastically supported beam equipped with friction devices at each end such that the natural frequencies of the beam could be altered by varying the friction load in the joints. It was concluded that an optimum friction force exists for minimum amplitude-frequency response, which is effective for several modes of vibration. Large reductions (up to 90%) in vibration amplitudes were obtained by optimising the friction damping.

An experimental study of damping in wood structures (9) indicates that the damping can be markedly increased by the proper design of necessary joints. Nailed joints can provide additional damping, special nailing devices increasing the total damping by more than an order of magnitude.

4. Theory

Although the dissipation of energy by interfacial slip in joints is a complex mechanism, it is generally accepted that the friction force generated between joint interfaces is usually;

a. Dependent on the materials in contact and their surface preparation;
b. Proportional to the normal force across the interface;
c. Substantially independent of the sliding speed and apparent area of contact;
d. Is greater just prior to relative motion occurring than during uniform relative motion.

The equations of motion of a structure with friction damping are thus non-linear; most attempts at analysis consist of linearising the equations in some way. A very useful method (10) is to calculate an equivalent viscous damping coefficient such that the energy dissipated by the friction and viscous dampers is the same. This has been shown (8) to give an acceptable qualitative analysis for macro slip. Some improvement on this method has been claimed (11) by replacing the coefficient of friction by a term which allows for changes in the coefficient with slip amplitude. Some success has also been obtained (5) by simply replacing the friction force by an equivalent harmonic force.

5. Conclusion

Frictional damping is a powerful method for vibration attenuation in structures. The main disadvantage, fretting corrosion, can be alleviated to some extent by suitable treatment of the contact surfaces. Linearised theoretical analysis appear adequate for the macro-slip conditions in the dry joint considered. As with elastic inserts, some relative motion between joint interfaces must be allowed for vibrational energy to be dissipated: indeed both forms of damping could be utilised in a single joint.

6. References

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