Proceedings of the Institute of Acoustics

VIBRATION TRANSMISSION THROUGH ADHESIVE JOINTS IN RODS

J L Horner
Department of Aeronautical and Automotive Engineering and Transport Studies,
University of Technology, Loughborough, Leicestershire, LE11 3TU, England.

1. INTRODUCTION

When constructing a joint in a structure it is usual to be interested in the mechanical strength of the connection. A joint in a structure may also be viewed as a discontinuity in the system. The presence of the discontinuity will affect the vibration behaviour by causing a proportion of the impinging wave energy on the joint to be reflected and a proportion to be transmitted. If the joint is a source of damping, some energy will be absorbed by the junction. Aside from affecting the damping of the structure, the presence of the joint will increase the number of degrees of freedom.

Investigations have been undertaken into welded joints, and the transmission properties of different types of welds compared [1] along with the respective damping properties. This showed that the number of dislocations affect the transmission properties. Bolted joints have also been analysed [2], with attention paid to the damping mechanisms and the relationship between damping and load on the joint. The structural properties of adhesives [3] are well documented with dynamic analysis centring on shock performance of joints. It has long been noted that adhesives in joints attenuate vibration, but little attention has been given to the comparative vibration behaviour of different types of adhesive joints.

2. TYPES OF ADHESIVE JOINT

Three types of joint were investigated experimentally, using two different adhesives. Figure 1 shows the three joints; a butt, a lap and a tenon. The joints were constructed at the centre of mild steel rods. Each rod was 1m long with a diameter of 25.4mm. The two adhesives used were an epoxy adhesive and a polyurethane adhesive which contained cyanoacrylate. To prevent a significant change in cross-section of the rod at the joint, minimum layers of adhesive were applied.

The butt joint was investigated because of the simplicity of connection. It is usually avoided in structural design due to the lack of strength in tension. In this investigation, it represented a joint with a single interface and hence a simple discontinuity. A stepped lap joint, rather than a simple lap, was tested in order to prevent a change in cross-section of the test rod at the joint. With a lap joint the direct tension in the rod is converted to shear. As adhesive bare far greater shear stresses than tensile stresses, this type of connection is most often used with adhesive. The tenon joint may be considered a derivative of the lap joint and again converts axial stresses to shear stresses. It is not a common form of structural adhesive joint and was used in this investigation as a complicated discontinuity, which would not significantly change the cross-section area of the rod.

Epoxy resin is one of the most common forms of structural adhesive and is recommended for use with ferrous alloys. It has good shear strength but, depending on type, may be prone to peel in impact situations. Most commercially available types have a cure time of 24 hours. The advantage of using this two part form of adhesive is that the long cure time allows careful preparation of the joint, with realignment possible after the surfaces have made contact. As epoxy resins act as fillers, the possibility of voids in the joint is reduced.

Polyurethane is considered to be a semi-structural adhesive and is recommended with reservation for structural joints in ferrous alloys. The presence of cyanoacrylate in the mix, results in an instant bond adhesive. For full structural strength the joint should be left for twenty four hours for the cure cycle to be complete. It has considerably less strength in shear than epoxy resins, and is used in those situations where an instant bond is necessary. The cure cycle is initiated by the exclusion of air, which leads to the possibility of voids.

3. EXPERIMENTAL INVESTIGATIONS

Each rod was subjected to both dynamic and static testing in the axial plane. The object of the vibration experiments was to determine the resonance behaviour of each rod and establish the effect of the presence of the joint. From the data obtained the damping in the joint could also be established for each configuration. The purpose of the tensile test was to determine the mechanical strength of the adhesive band and to confirm that vibration testing had been undertaken on mechanically sound connections.

3.1 Frequency Response Functions Measurements.

The jointed rods, plus a solid rod of the same material and dimensions were subjected to axial random excitation in the frequency range 1Hz to 12.8Hz, whilst suspended in a free-free manner. An electrodynamic shaker was used to excite the rods and a force transducer and accelerometer were used to measure the response. From measurements of the transfer inertance (frequency domain ratio of acceleration to force) the resonance frequencies of the rods could be identified. For the solid rod (Figure 2) four dominant resonances peaks were observed. Table 1 compares these resonances with natural frequencies predicted using compressive wave theory for a free-free rod. The smaller resonance peaks in Figure 2 correspond to flexural modes of the rod.

Natural Frequency $$fn = \frac{n}{2l}\sqrt{\frac{E}{\rho}}$$

Mode	fn (Hz)	
n	Predicted	Measured
1	2717	2704
2	5434	5416
3	8151	8144
4	10868	10864

Table 1: Solid Rod

Each of the jointed rods was subjected to random excitation over the 1Hz to 12.8Hz frequency region. Figures 3-8 show the measured transfer inertance for each joint/adhesive combination. The first longitudinal mode for each joint/adhesive combination occurs at approximately the same frequency (2680Hz) and indicates that the type of joint has little effect on the first mode. By comparison, the measured second resonance frequencies of the jointed rods fall in to two regions. The butt and lap joints had a second mode at approximately 5390Hz whereas the tenon joints second resonance was at 5530Hz. This represents a 5% change in stiffness between the tenon joint and the butt and lap joints. It is also interesting to note the general drop in level in the frequency response function for the tenon joint. Comparison of modes after the second longitudinal resonance becomes less simple due to the number of modes in the frequency region 7.5 - 12kHz increasing for the butt joint and the lap joint.

Examination of the resonance frequencies for the butt and lap joints in the region 7.5 - 12kHz, revealed that modes were occurring in pairs. For example, Figure 3 showed the response of the butt joint constructed using epoxy resin. Two resonance frequencies occurred at 7892Hz and 8032Hz, with another pair occurring at 10408Hz and 11330Hz. Figure 4 (butt joint/polyurethane) did not exhibit this behaviour, but it was felt that the poor signal to noise ratio in the 10 - 12kHz region could have masked a possible pair of modes.

The two lapped joints exhibited pronounced pairs of modes. Figure 5 illustrated the response of the lap/epoxy resin joint and showed three modes occurring in 8kHz region and a single, very lightly damped mode at 10852Hz. Similarly, Figure 6 (lap/polyurethane) showed a pair of modes around 8kHz and a pair around 11kHz.

The frequency response function of the two tenon joints were shown in Figures 7 and 8. Both exhibited significantly lower levels of response than the other two joint types. It should also be noted, that although the four dominant longitudinal modes were present, other resonance peaks could be observed in the figures. These corresponded to flexural modes of the rod.

The shaker was aligned along the axis of the rod to ensure only axial excitation was present and the tests were repeated three times. These flexural modes were considered to be a function of the joint type and not the excitation process. Although the flexural modes were present in both Figures 7 and 8, the tenon joint, attached using epoxy resin, exhibited the dominant flexural behaviour.

By using the half power point method it was possible to calculate the damping ratio for each mode of the different joint configurations.

$$\text{Damping Ratio} \quad \zeta = \frac{f_2 - f_1}{2fn}$$

where f_1 and f_2 are the half power frequencies. Table 2 shows the damping ratios for the first two modes of each rod.

Joint Adhesive	Damping Ratio n = 1	n = 2
Butt Epoxy Resin	0.013	0.006
Butt Polyurethane	0.030	0.006
Lap Epoxy Resin	0.013	0.005
Lap Polyurethane	0.013	0.008
Tenon Epoxy Resin	0.13	0.005
Tenon Polyurethane	0.011	0.016

Table 2: Measured Damping Ratio

With the exception of the tenon/polyurethane combination, the type of joint and/or adhesive had little effect on damping ratio. The tensile tests, detailed in Section 3.2, showed that the tenon/polyurethane rod exhibited uncharacteristically high tensile strength, due to friction between the joint surfaces. This phenomenon would also account for the high damping ratio for the second mode.

3.2 Tensile Strength Measurements.

In order to ascertain the mechanical integrity of each joint used in the investigation, tensile testing was undertaken. After the frequency measurements were completed, each rod was cut to a shorter length in order to fit into a tensometer. The tensile test specimens were 30cm long, with the joints in the middle of the specimen. In order for the chuck in the tensometer to grip the test specimens, a high tension threaded bar was inserted into each end. Each joint/adhesive combination was tested to destruction. For the butt and lap, this was easily observed by sudden failure of the joint. Tensile testing of the tenon joint proved to be more difficult as the test pieces did not separate dramatically, but tended to slide apart. All test pieces failed at the joint, either by fracture of the adhesive bond or peel from one of the metallic surfaces. Table 3, below shows a summary of the tensile test results.

Joint/Adhesive	Ultimate Load (tons)
Butt - Epoxy Resin	0.66
Butt - Polyurethane	0.27
Lap - Epoxy Resin	1.19
Lap - Polyurethane	0.97
Tenon - Epoxy Resin	1.70
Tenon - Polyurethane	1.69

Table 3: Ultimate Tensile Load

As expected, the butt joint withstood the least tensile load. For both butt and lap joints, the epoxy resin bend was stronger than the polyurethane bond. Again this was as expected for the adhesive types. The equal tensile load borne by the tenon joints was felt to be a function of friction between the joint surfaces rather than adhesive strength. In order to minimise increases in cross-sectional area of test pieces, glue lines were kept as thin as possible. On inspection, the tenon joint had significant mechanical strength on press-fit situation with no adhesive present.

4. DISCUSSION

From the tensile test results, it was possible to determine that all joints were mechanically sound and with epoxy resin connections proving stronger in tension than polyurethane connections.

It was noted that the type of adhesive bond did not affect the strength of the tenon joints, due to the high friction effects between the joint surfaces. Examination of measured frequency response functions showed that the first mode of each rod was unaffected by the joint/adhesive combination. As the wavelength at 2680hz was 1.92m, this result was not surprising. At the second mode, of the rods, the wavelength was approximately 0.96m. At this mode, the joint types exhibit two forms of behaviour, with the butt and lap joint having resonances around 5390Hz and the tenon at 5530Hz. As the lap and tenon were of the same physical dimensions (25.4mm long) this result was unexpected. Inspection of the transfer inertance for the tenon joint, showed significant flexural motion was present. Comparison of the resonance frequencies with natural frequencies predicted using Euler-Bernoulli beam theory for a free-free beam show the measured frequencies were not associated with a uniform beam. The tenon joint was inducing flexural motion in the axially excited rod and this accounted for the general drop in level in the measured transfer inertance.

The pairs of resonance frequencies observed in the measured transfer inertances for the lap and butt joints occurred approximately at the same frequency as the third and fourth modes of the solid rod. By considering compressive wave theory for rods, it was possible to establish that the first pair of resonances were associated with each half of the rod behaving in a fixed-free manner. The third mode of a free-free rod of length l will occur at the same frequency as the second mode of a free-fixed rod of length $^{l}/_{2}$ made of the same material. For the lap/epoxy resin rod, a Solid rod mode also occurs at 8kHz. Similarly the second pair of modes observed in the butt/epoxy resin and lap/polyurethane responses correspond to free-free response of a rod half the length of the test piece.

Two discrete modes are measured which indicates that reflection is not occurring midway in the rod. For the lap joint results, the frequency spacing in each pair of modes can be related directly to the dimensions of the joint. It was found that waves were being reflected from one end of the joint only.

In conclusion, the type of joint has little effect on the frequency response of the rods at low wave numbers. As the wave number increased the two sections of the jointed rods behaved first as fixed-free rods and then as the frequency increased as free-free rods. Interestingly the rods did not subdivide into equal lengths, possibly due to dislocations in the rod. With a tenon joint, flexural waves were induced in the structure when it was excited axially. This may be considered a function of the axial stresses in the joint being converted to shear stresses.

ACKNOWLEDGEMENT

The author would like to acknowledge the assistance of M.P. Wallwork in the measurements of the results presented in this paper.

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APPENDIX

Nomenclature

E - Modulus of elasticity
f_n - Natural frequency of the nth mode
l - Length of rod
n - Mode number
ζ - Damping ratio
ρ - Density

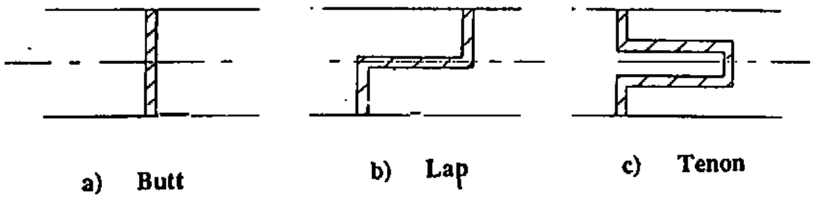

Figure 1: Joint Types

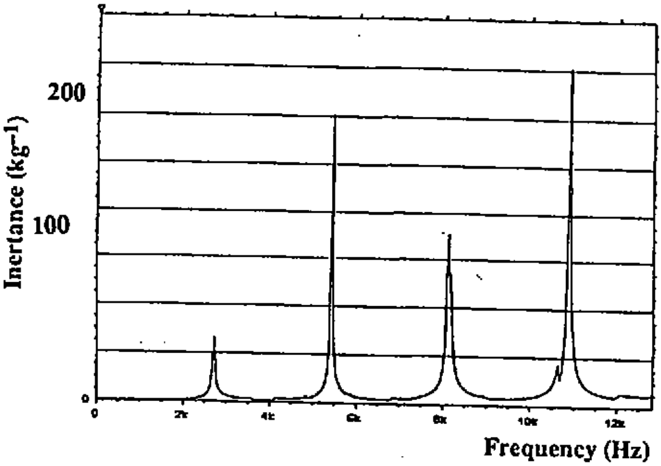

Figure 2: Transfer Inertance Solid Rod

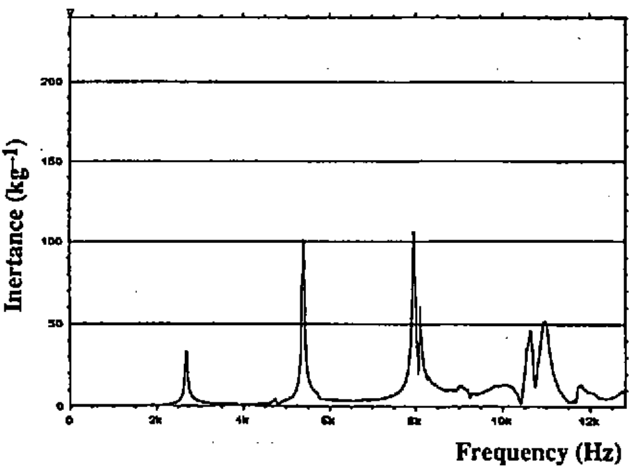

Figure 3: Transfer Inertance Butt/Epoxy Resin

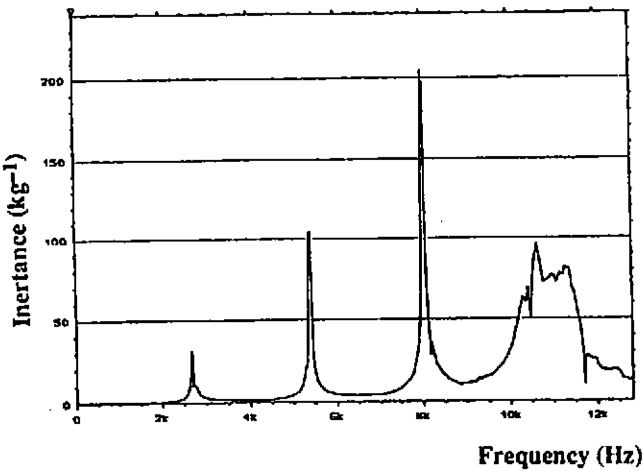

Figure 4: Transfer Inertance Butt/Polyurethane

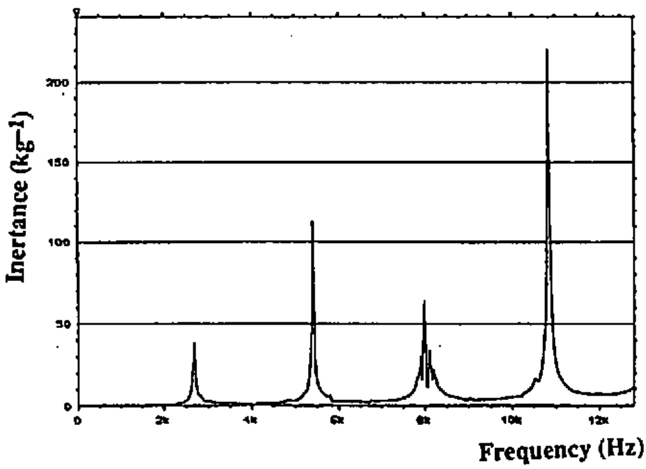

Figure 5: Transfer Inertance Lap/Epoxy Resin

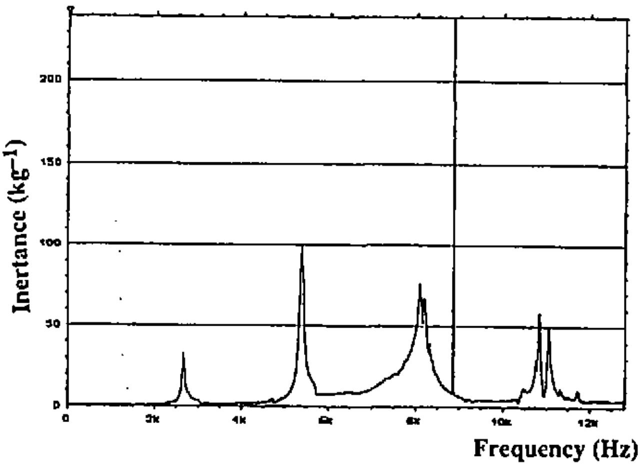

Figure 6: Transfer Inertance Lap/Polyurethane

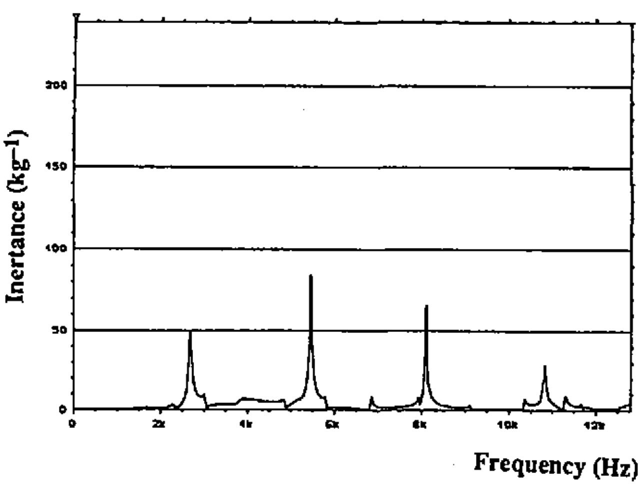

Figure 7: Transfer Inertance Tenon/Epoxy Resin

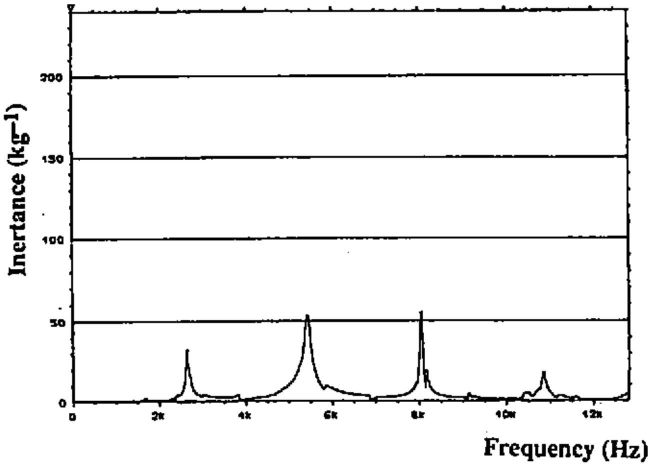

Figure 8: Transfer Inertance Tenon/Polyurethane

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VIBRATIONAL POWER TRANSMISSION IN ONE-DIMENSIONAL STRUCTURES FITTED WITH ASYMMETRIC DISCONTINUITIES

P Clark (1) and R G White (1)

(1) Institute of Sound and Vibration Research, University of Southampton, Southampton, UK

When attempting to control the vibration transmitted from machinery installations, perhaps with a view to reducing the unwanted radiation of noise at a point remote from the source, it is essential that all possible transmission paths are considered. With the majority of installations, one-dimensional structures such as beams, pipework vibrating at low frequencies and other mechanical linkages, form some of the main vibration paths which bypass isolator systems. In addition to this, these structures usually contain discontinuities which significantly affect the vibration characteristics of the complete installation. In this study, discontinuities representative of vibration control devices mounted asymmetrically on a beam-like structure are considered with particular reference to vibrational power transmission and wave-type conversion.

NOTATION

A	=	cross-sectional area of beam
A_f^*	=	amplitude of flexural wave
A_l^*	=	amplitude of longitudinal wave
a	=	moment arm length
E	=	Young's modulus of elasticity
I	=	second moment of area of beam
k_f	=	flexural wavenumber
k_l	=	longitudinal wavenumbet
k_d	=	neutralizer spring stiffness
μ	=	ratio of neutralizer mass to beam mass per unit length
m_d	=	neutralizer mass
π	=	neutralizer spring loss factor
ρ	=	density of the beam
ω	=	excitation frequency in radians per second
ω_d	=	undamped natural frequency of the neutralizer in radians per second
Ω_d	=	ω/ω_d

* Additional subscripts:
- 3 – reflected wave
- 4 – transmitted wave
- i – incident wave