Tangential slip noise of V-ribbed belts

K W Dalgarno[1]*, **R B Moore**[2] and **A J Day**[2]
[1]School of Mechanical Engineering, The University of Leeds, UK
[2]Department of Mechanical and Manufacturing Engineering, University of Bradford, UK

Abstract: This paper reports the results of a study into V-ribbed belt noise generated as a result of tangential belt slip. The results of experimental studies to identify the belt operating conditions associated with belt noise are presented, together with the results of analytical studies to identify the mechanism of noise generation. It is concluded that tangential slip V-ribbed belt noise generation is controlled only by the amount of slip, and that the mechanism of noise generation is harmonic excitation of the fundamental vibration mode of the belt, with stick–slip frictional behaviour providing the impetus for the vibration.

Keywords: power transmission belts, belt noise, noise analysis, belt slip

NOTATION

s	belt slip
ω_r	driver pulley speed
$\Delta\omega$	difference in speed between driver and driven pulleys

1 INTRODUCTION

V-ribbed belts have been used as power transmission elements since the 1950s when they were developed to provide a combination of high flexibility and high power transmission capacity for drives where small pulley diameters were required. Figure 1 shows the construction of these belts schematically; the main belt constituents are polyester cords as the tension member, a cushion elastomer compound which envelops the cords, and a rib elastomer compound which forms the belt ribs, and which may be stiffened through the use of short fibre reinforcement in the axial direction. The flexibility of the belts arises from the small section depth, and the power transmission capacity from the V-shaped ribs, which develop traction in a similar fashion to traditional V-belts.

Given that a belt has the power capacity required of a drive, belt wear and noise are the mechanisms by which a V-ribbed belt may be considered to fail. Belt wear and power capacity have been studied by a number of authors [**1**–**4**], but studies of V-ribbed belt noise are rare. Connell and Rorrer [**5**] present the only detailed study of V-ribbed belt noise and suggest that radial slip (occurring as the belt moves into the pulley grooves) and tangential slip of the belt relative to the pulley can both lead to friction-induced vibration and belt noise. Connell and Rorrer studied belt noise arising from radial slip of the belt relative to the pulley (with the belt operating under no torque conditions to minimize tangential slip) and identify three distinct noise generation regimes: span vibration (50–500 Hz), stick–slip (800–3500 Hz), and harmonic oscillation (4400–5600 Hz), with the span vibration and harmonic oscillation modes excited by radial slip (analyses of belt span vibration may be found in references [**6**] to [**8**]).

This paper presents the results of an investigation of V-ribbed belt noise arising from tangential slip between belt and pulley. The starting point in this study was an experimental evaluation of noise generation in V-ribbed belts, and this is described in the next section.

2 EXPERIMENTATION

Two sets of tests were carried out to investigate noise generation of the belts, the first gradually increased the level of slip the belts experienced to determine under what conditions the belts generated noise, while the second aimed to recreate in a controlled manner those conditions under which noise was observed to provide noise signals for further analysis.

The MS was received on 6 July 1998 and was accepted after revision for publication on 12 October 1998.

** Corresponding author: School of Mechanical Engineering, The University of Leeds, Leeds LS2 9JT, UK.*

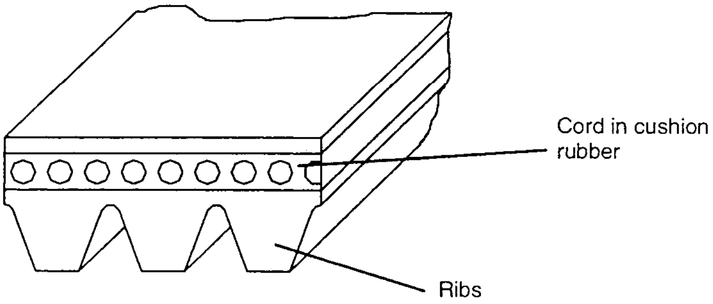


Fig. 1 V-ribbed belt cross-section showing belt construction

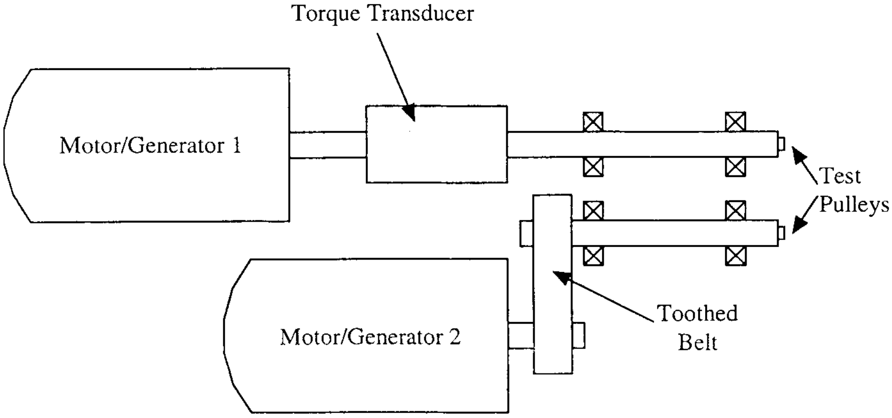


Fig. 2 V-ribbed belt testing dynamometer

2.1 Belt slip tests

2.1.1 *Equipment*

The tests were conducted on a V-ribbed belt dynamometer, shown schematically in Fig. 2. The dynamometer is described in full elsewhere [**9**] and so is only briefly described here. A motor and generator mounted in parallel provide the driver and driven pulley torques to the belt system, with an in-line non-contacting torque transducer used to measure the torque supplied to the system. The motor speed and generator braking torque were controlled through separate drive units. The pulley layout used during testing is shown in Fig. 3 and was derived from standard test conditions [**10**]. The belt tension was set and maintained through the tension pulley shown in Fig. 3, with a load cell fixed such that the direction of the measured force bisected the angle of wrap on the pulley. The dynamometer was designed so that both drive units could operate either as a motor or a generator, and with the positioning of tension and idler pulleys variable so that most belt/pulley layouts could be accommodated. The load and speed of both motor and generator and the output from the torque and tension transducers were all stored on a PC using data acquisition software. When a new layout was employed in testing, a belt would be run-in for 50 h with the new pulley configuration in place, to allow for conditioning of pulley groove surfaces and any other transient effects.

Table 1 Differences between belt types. Modulus values are 10 per cent secant moduli from tensile tests carried out at 45 °C, and density values are also measured at 45 °C

Belt type	A	B	C
Nominal belt length (mm)	1400	986	986
Elastomer compound modulus (MN/m^2)	7.6	11.1	5.6
Elastomer compound density (kg/m^3)	1230	1160	1350

2.1.2 *Belts and pulleys*

The geometry of the belts and pulleys used in this study was a three-rib K section, as defined in reference [**10**]. Three different belts were used, all identical with the exception of the rib elastomer and the belt length. Table 1 shows the variations in make-up between the three belts. All three types of belt were manufactured with the ribs cut rather than ground, and all three had the same polyester reinforcing cord.

2.1.3 *Procedure*

The procedure for the belt slip tests was to drive the belt with a set tight side tension, torque and speed, while recording the speed of the driven pulley to assess the amount of slip. The belt slip, s, is defined as

$$s = \frac{\Delta\omega}{\omega_r} \tag{1}$$

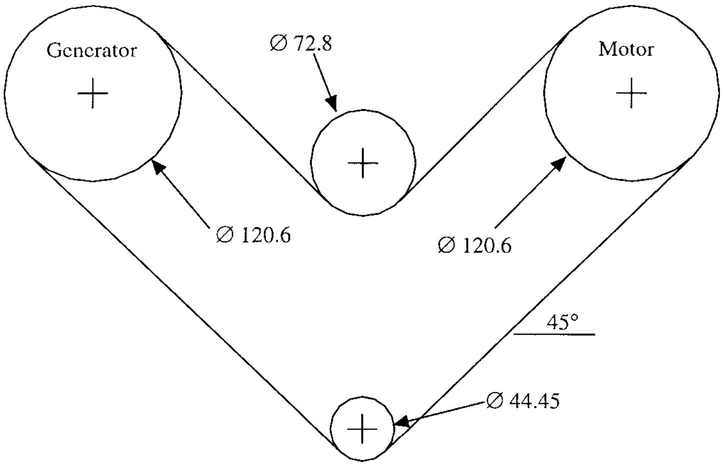


Fig. 3 Pulley layout for testing: dimensions in mm, diameters are PCD

where ω_r is the speed of the driver pulley and $\Delta\omega$ is the difference in speed between the driver and driven pulleys. Within the tests the torque range was 5–13 N m, the tight side tension on the driven/driver pulleys ranged from 200 to 800 N and the belt speed ranged from 100 to 1100 r/min. The tests were carried out at room temperature.

2.1.4 Results

Within the belt slip tests two distinct regions of behaviour were seen. When the belt slip was below 0.1 the drive was stable and results with a repeatability of ±1 per cent were achieved. No noise generation was observed at slip levels below 0.1. At slip levels of between 0.1 and 0.7 the drive was unstable and the repeatability associated with results was up to ±15 per cent. Tests resulting in slip levels of between 0.1 and 0.7 were associated with sustained noise generation. Figure 4 shows a typical set of results from the belt slip tests for belt type A. The results show that the belt slip increases as the total tension decreases for a given torque level, and that the belt slip increases with torque for a given level of tension, results that are in line with observations of previous authors [**2**, **3**]. Previous authors [**3**, **11**] have also noted a decrease in the level of belt slip with run time, an observation that does not agree with the results shown in Fig. 5. The reduction in belt slip has previously been ascribed to modifications in the belt rib profile (providing a 'matched' belt/pulley profile) or changes in the belt rib surface condition which may produce an increase in the coefficient of friction between belt and pulley. In this case the conditions at which the belts were run before having the speed loss reassessed are more severe than those used by previous authors, and it is considered that the results shown in Fig. 5 are representative of the effect of accelerated wear, rather than running in of the belt. Figure 6 shows a comparison of the belt slip characteristics of all three belts considered in this study.

2.2 Controlled gross slip tests

The results of the tests reported above indicated that belt noise was associated with gross tangential slip in the

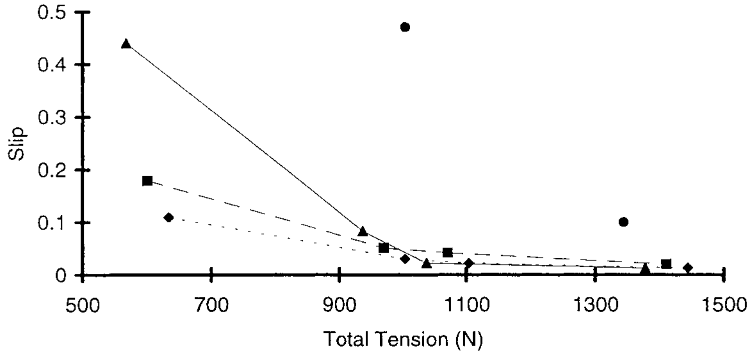


Fig. 4 Belt slip test results for belt type A. Torque values: ◆ 7 N m, ■ 9 N m, ▲ 11 N m, ● 13 N m; driver pulley speed 800 r/min; room temperature

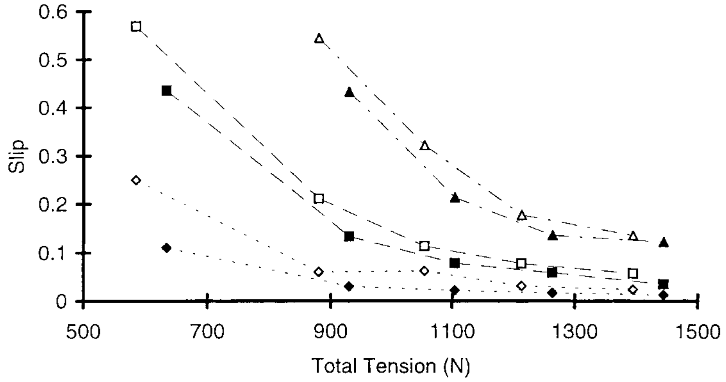


Fig. 5 Effect of run time on belt slip for belt type A: ◆ new belts, ■ belts run for 200 h, ▲ belts run for 400 h; filled symbols 7 N m torque, hollow symbols 10 N m torque; other conditions as in Fig. 4

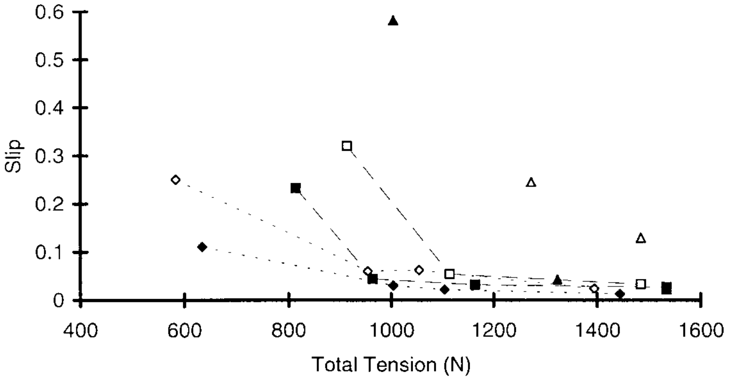


Fig. 6 Belt slip results for belt types A (◆), B (■) and C (▲): filled symbols 7 N m torque, hollow symbols 10 N m torque; other conditions as in Fig. 4

drive. To investigate this effect further a series of tests designed to create gross slip in the drive were carried out.

2.2.1 *Procedure*

The tests were again carried out on the V-ribbed belt testing dynamometer, as described in Section 2.1.1, with the pulley layout shown in Fig. 3. The tests started with the belt at rest. The motor was then accelerated at 1000 r/min per second to a preset speed between 200 and 1000 r/min. In any given test the torque and tight side tension were kept constant, with the values selected (on the basis of the tests described in Section 2.1) as those likely to generate gross tangential slip. Figure 7 shows typical driver/driven pulley speeds in the tests, indicating that gross slip was generated. An audio recording of the noise generated during each test was made. These recordings were subsequently digitized and a fast Fourier transform used to provide noise data in frequency/amplitude form. Background noise to the tests was characterized by running the dynamometer without a test belt, and the noise signal resulting is shown in Fig. 8. These tests were again carried out at room temperature, although the temperature of the rib elastomer was measured after testing and was found to be 45 ± 5 °C in all cases.

2.2.2 *Results*

Figure 9 shows the noise signals recorded at various levels of slip throughout the test shown in Fig. 7. Significant increases in noise over the background level are seen at 90 and 60 per cent slip, with less at 30 per cent slip, and no increased noise over the background level at 10 per cent slip. At 90 and 60 per cent slip (and to a lesser extent at 30 per cent slip) clear peaks in the noise signal can be seen at around 3000 Hz. There are also peaks at 3000 Hz shown in the background noise, albeit at a much reduced level, the source of which was identified as a V-belt driving an oil pump which provided lubrication for the bearings. The oil pump drive and the test belt drive were not mechanically connected in any way so it was considered unlikely that the increased noise amplitude was arising from the oil pump drive. As the noise level indicated from the tests was greater than that from the background noise, no attempt was made to correct for the background noise, and the peaks shown in Fig. 9a and b were assumed to arise from test belt noise, and the noise was characterized by the frequency associated with the peak of highest amplitude.

Figure 10 shows the results of a series of tests with previously unused type A belts designed to investigate the effect of the slip level, the belt tension and the torque

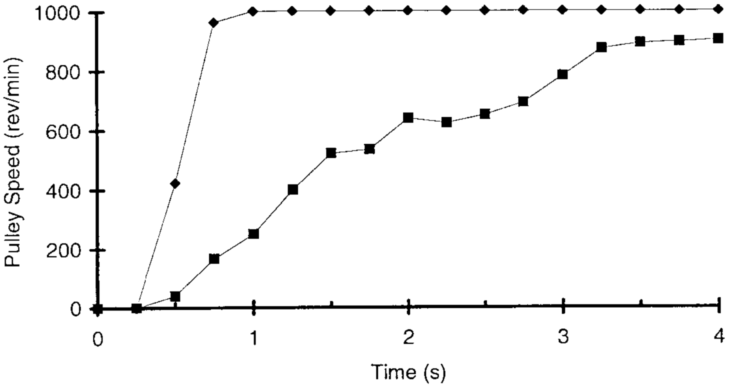


Fig. 7 Pulley speed during noise tests: ◆ driver pulley, ■ driven pulley; torque 11.5 N m; total tension 1200 N; room temperature

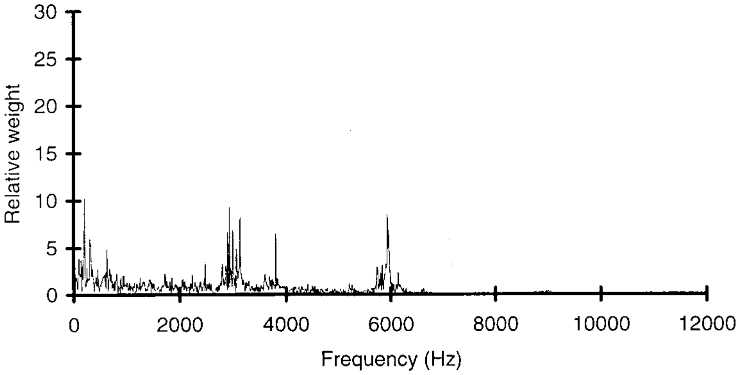


Fig. 8 Background noise spectrum

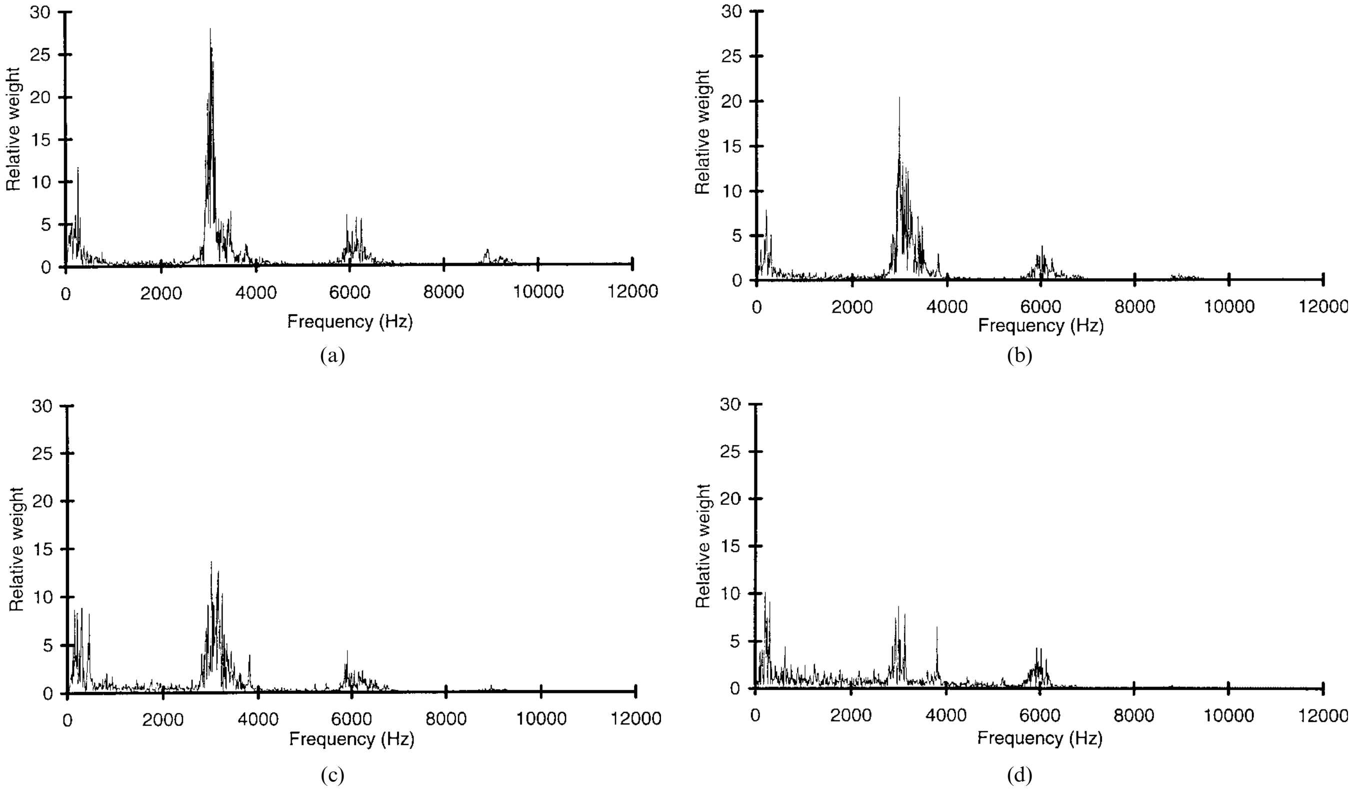
on the frequency of the noise produced by the belt. The graphs show that the three variables have little effect on the frequency of the noise, and the conclusion drawn from the graphs was that the noise frequency was independent of slip, torque and tension. The average frequency recorded for belt type A from all test results was 2973 Hz, with all test results encompassed within a ± 125 Hz band. The only exception to this was found to be the first test carried out with a 'cold' belt, which gave an average frequency of 3538 Hz before settling down over a period of 5 s to a value within the band indicated above. Tests carried out on a previously used type A belt gave an average frequency value of 2968 Hz, very close to that for previously unused belts, and tests on type B and type C belts gave average frequency values of 3808 and 2580 Hz respectively.

3 V-RIBBED BELT VIBRATIONAL MODES

From the tests described in Section 2.2 the conclusion was that the frequency of belt noise arising from gross tangential belt slip was independent of torque, tension and slip level. The changes in observed frequency between belt types A, B and C were therefore assumed to arise from differences between the elastomer compounds in the belts (all other aspects of belt construction bar length being the same). To investigate the effect that changes in the material properties of the elastomer compound would have on the vibrational modes of the belts, eigenvalue extraction using finite element techniques has been employed.

3.1 Finite element model

The finite element model employed in the analysis can be seen in Fig. 11. First-order three- and four-noded plane stress elements were used, and the analysis was run using the ABAQUS finite element code [**12**]. The use of a plane stress analysis was justified by considering Fig. 10b, which indicates that the noise response was independent of the tension applied to the belt. In practice, as a belt goes round a pulley, significant stresses and strains will be developed perpendicular to the plane shown in Fig. 11. The mesh used was coarse but was found to be refined enough adequately to represent the vibrational modes of interest. One layer of elements was



(a) (b) (c) (d)

Fig. 9 Noise spectrum for type A belt at (a) 90 per cent slip, (b) 60 per cent slip, (c) 30 per cent slip and (d) 10 per cent slip: other conditions as in Fig. 7

used to represent the cord layer in the belt, as indicated in Fig. 11, with all other elements representing the elastomer compound and given the material property data shown in Table 1 for belts A, B and C respectively. The properties of the cord layer were developed from volume fraction theory [**13**] to include appropriate contributions from both the cord and the elastomer compound in this region. This process resulted in a value for the Young's modulus of this region of 2.1 GN/m^2, and a density of 580 kg/m^3. With the geometry and material properties of the structure defined, the natural frequencies of vibration of the system can then be developed through eigenvalue extraction, in this case utilizing subspace iteration routines embedded within the finite element code [**14**].

3.2 Finite element results

Table 2 shows the predicted natural frequencies for the first vibrational mode for each belt type, together with the measured noise frequency for each belt type. Agreement between the two sets of figures is within 5 per cent. Figure 12 shows the mode shape exhibited by the belts at the fundamental natural frequency.

Table 2 Comparison of noise frequency and predicted fundamental natural frequency

Belt type	A	B	C
Measured noise frequency (Hz)	2973	3808	2580
Predicted frequency of first vibration mode (Hz)	3108	3720	2601

4 DISCUSSION

4.1 Noise generation mechanism

The results above suggest that the noise generation mechanism for V-ribbed belts undergoing tangential slip is one of self-excited vibration, with stick–slip frictional contact between belt and pulley assumed to be inducing the belt to oscillate at its fundamental natural frequency. This mechanism is the same as that observed in noise arising from radial belt slip [**5**]. However, radial belt slip was seen to excite higher-order modes of vibration in the belt such that the vibration mode was effectively a single degree-of-freedom system with each rib oscillating independently. This in effect meant that the frequency of the belt noise was unchanged by the number of ribs on the belt. With tangential slip noise generation in V-ribbed belts it is the fundamental mode of vibration that is excited and so the frequency of the belt noise is expected to change with the number of belt ribs. In practice, however, the change in the fundamental frequency is not great (the predicted fundamental frequency for a

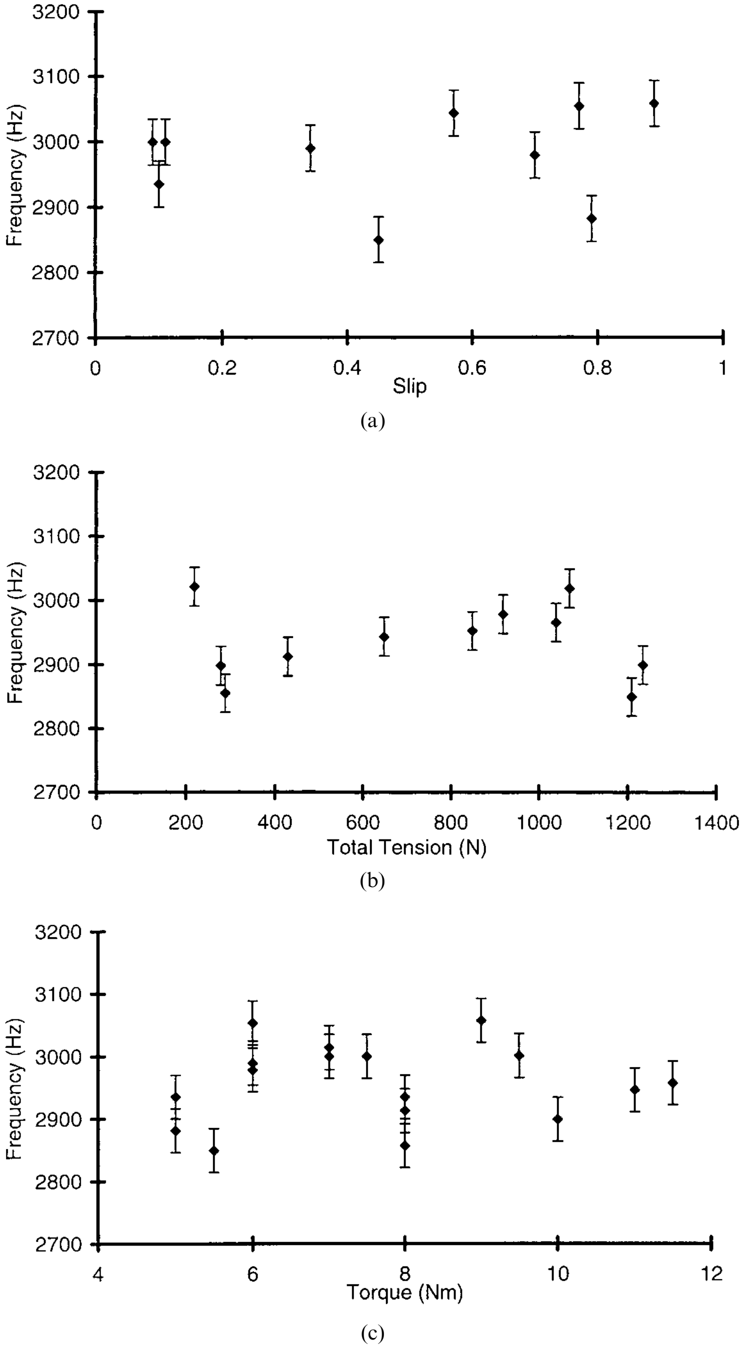


Fig. 10 Effect of (a) slip level, (b) tension level and (c) torque level on noise frequency for belt type A

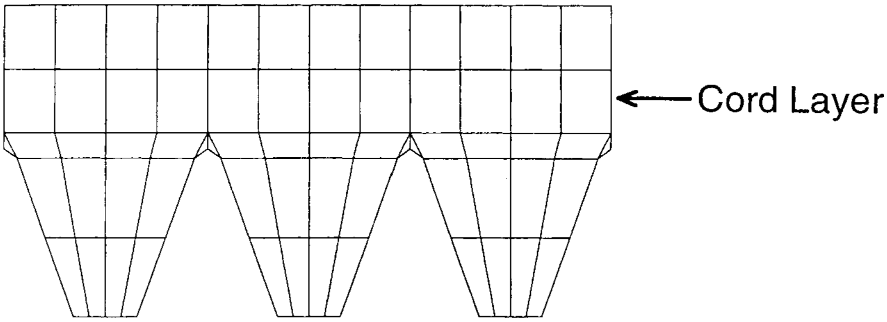


Fig. 11 Finite element mesh for modal analysis

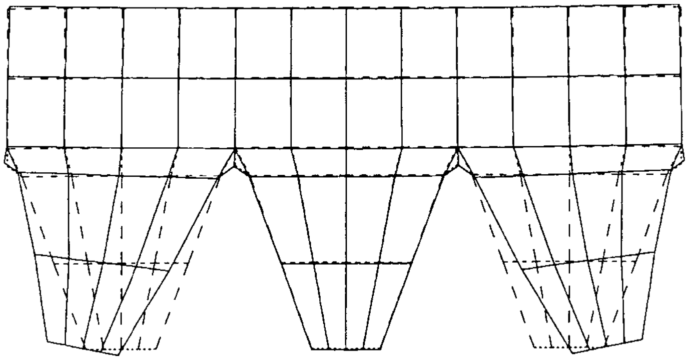


Fig. 12 Three-rib belt first mode shape: dashed lines indicate original mesh

four-rib type A belt is 2812 Hz, as opposed to 3108 Hz for a three-rib belt), and so changes in noise frequency with belt width are expected to be small compared with the changes in frequency that resulted from a change in elastomer compound material between belts A, B and C. That the mechanisms of noise generation are the same does mean that modal analysis of the belts allows the belt noise frequencies to be predicted, with the excitation of the different modes by radial and tangential slip providing a method to differentiate between the two noise sources. The sensitivity of the natural frequency to material properties also provides an explanation for the scatter in the experimental measurements of noise frequency, which is considered to arise through small variations in material properties as a result of small changes in belt temperature.

4.2 Implications for industrial drives

In terms of avoiding belt noise generated by tangential slip, the clear conclusion to come from this work is that high levels of slip should be avoided. As high slip levels are likely to limit the life of the belts severely, this is not a particularly restricting constraint on the operation of the belts, although the amount of slip a belt sees does increase over time as the belt wears. One area where tangential slip noise has been observed to cause problems in drives is where additional loads are put into the belt drive while it is in operation. One common example of this is the use of V-ribbed belts as auxiliary drives in vehicles with the air conditioning system driven from the belt. As the air conditioning unit is not always operating, it can, when turned on, add an extra load to a belt that is already transmitting power, and belt noise can result. The belt noise has normally been observed to be transient, disappearing after the torques in the system have stabilized. The work reported here would suggest that, while the arrival of such a load into the system is associated with substantial levels of slip, belt noise is inevitable. Altering the belt elastomer compound would allow the frequency of the noise to be altered, if this were of value, but perhaps the only method by which the noise could be avoided would be a 'soft start' on the air conditioning system in order to limit the rate at which the load was introduced to the system and hence limit the slip.

5 CONCLUSIONS

1. The occurrence of tangential slip noise in V-ribbed belts is dependent only on the level of slip. For the pulley layout shown in Fig. 3 with belt lengths of 986 and 1400 mm, tangential slip noise was only observed at slip levels greater than 10 per cent.
2. The mechanism of belt noise generation from tangential slip is considered to be harmonic excitation of the fundamental vibration mode of the belt, with stick–slip frictional behaviour providing the impetus for the vibration. This means that the frequency of the noise is independent of slip level (providing sufficient slip to generate noise is present), torque, tension or belt speed as the vibration associated with the noise is at the fundamental natural frequency of the belt.

ACKNOWLEDGEMENTS

The work reported here was supported by the EPSRC and industrial sponsors. The authors are grateful to the EPSRC and the sponsors for their support.

REFERENCES

1 **Hansson, H.** Geometry conditions for good power capacity in a V-ribbed belt drive. *Trans. ASME, J. Mech. Des.*, 1990, **112**, 437–441.

2 **Gerbert, G.** Gross slip limit of V-ribbed belts. Paper presented at the IMechE European Seminar on *Belt Drives*, London, 22 February 1994 (Mechanical Engineering Publications, London).

3 **Tabatabaei, S. M., Childs, T. H. C.** and **Yu, D.** Mechanical performance of V-ribbed belt drives (experimental investigation). SAE paper 970006, 1997.

4 **Yu, D., Childs, T. H. C.** and **Dalgarno, K. W.** Experimental and finite element studies of the running of V-ribbed belts in pulley grooves. *Proc. Instn Mech. Engrs, Part C, Journal of Mechanical Engineering Science*, 1998, **212**(C5), 343–354.

5 **Connell, J. E.** and **Rorrer, R. A. L.** Friction-induced vibration in V-ribbed belt applications. ASME DE-Vol. 49, 1992, pp. 75–85.

6 **Gasper, R. G. S.** and **Hawker, L. E.** Resonance frequency prediction of automotive serpentine belt drive systems by computer modelling. ASME DE-Vol. 18-2, 1989, pp. 13–16.

7 **Debbabi, C., Simon, J. M.** and **Vialard, S.** New dynamic model of poly-V power transmission belt: application to internal combustion engines. In Proceedings of 23rd International Symposium on *Automotive Technology and Automation*, Vienna, Austria, 3–7 December 1990, Vol. 3, pp. 63–68.

8 **Yue, G.** Vibration of belt strand. In Proceedings of International Conference on *Belt Transmissions*, Osaka, Japan, 2–3 December 1991 (Japanese Society of Mechanical Engineers).

9 **Moore, R. B.** Materials characterisation and performance prediction in power transmission belts. PhD thesis, University of Bradford, UK, 1997.

10 Automotive V-ribbed belt drives and test methods. SAE J1596, June 1989.

11 **Hansson, H.** Mechanics of V-ribbed belt drives. Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden, Report 1989-09-27, 1989.

12 *ABAQUS Users Manual, Version 5.6*, 1996 (Hibbitt, Karlsson and Sorenson Inc.).

13 **Cembrola, R. J.** and **Dudek, T. J.** Cord/rubber material properties. *Rubber Chem. and Technol.*, 1975, **58**, 830–856.

14 *ABAQUS Theory Manual, Version 5.6*, 1996 (Hibbitt, Karlsson and Sorenson Inc.).