The source of Acoustic Emission during meshing of spur gears

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Abstract

Condition monitoring of gears with vibration analysis and Spectrometric Oil Analysis Programs (SOAP) are widely accepted and used in the military aviation industry. Whilst the literature to date has shown the application of the Acoustic Emission (AE) technique to gearbox health monitoring still be in its infancy, there exist opportunities to develop the technique into a complementary diagnostic tool. In developing such a tool, it is imperative that an understanding of the source of AE activity is established. This paper presents experimental results that explore the AE source during a gear mesh and has led to quite unique and significant observations.

Keyword: Acoustic Emission, asperity contact**,** condition monitoring, gear defect diagnosis, machine health monitoring, rolling friction, sliding friction.

Literature reviews

Application of vibration analysis to gear fault diagnosis and monitoring has been widely investigated and its usage in industry is well established. This is particularly reflected in the aviation industry where helicopter engines, transmission systems, drive trains and rotor systems have adopted vibration analysis for health monitoring. However, research in the application of AE to gear fault detection and monitoring is limited.

The most common failures encountered in operational gearboxes include micro-pitting, pitting, scuffing and abrasive wear. Although tooth fracture and bending fatigue are rare, the criticality of such a failure has drawn huge attention from researchers. In examination of the AE technique on these failure modes, most researchers have opted for simulated pit defects.

Singh [1, 2], Tandon [3] and Siores [4] performed their experiments using simulated pits, whilst Toutountzakis [5], Sentoku [6] and Miyachika [7] allowed natural defects such as pitting to occur during the tests. The conclusion drawn from all these experiments were encouraging; AE technique was able to detect both seeded and natural defects. Among these researchers, only Toutountzakis and Sentoku employed a slip ring to transmit the AE data from the rotating AE sensor to the acquisition systems, thereby offering a direct transmission path. Others mounted their AE sensors on the bearing or gearbox casing and, claimed successful identification of defective gears.

The papers reviewed have illustrated the potential and viability of the AE technique in becoming a useful diagnostic tool in condition monitoring of gears. However, none have investigated the source of AE activity during the gear mesh. An understanding of the fundamental AE source mechanism in meshing gears is of vital importance in developing this technique.

Observation of AE bursts during gear mesh

AE data was recorded during simulated defect gear tests. An interesting observation was the AE transients associated with the gear mesh. With a sampling rate of 10 MHz and rotational speed of approximately 742 rpm, only 16 meshing teeth signatures were recorded per acquisition window. Figure 1 shows the time domain of an AE signature recorded during the tests under two different load conditions clearly showing the AE transient response associated with gear meshing of 16 teeth. This AE transient response led the authors to investigate the possible source of AE activity due to the meshing gear. The results presented were acquired from the AE sensor mounted on the pinion wheel and AE data was captured with a commercial data acquisition card (PAC) via a slip ring.

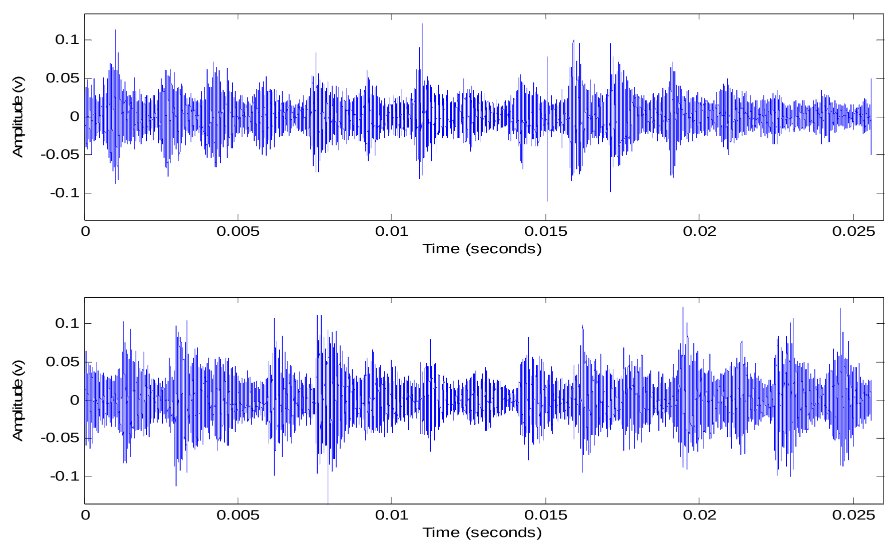

Figure 1 **Time domain of an AE signature showing clearly the AE transient response associated with gear meshing of 16 teeth for the rotational speed of 745 rpm under various loads (pre-amplification 20dB)**

AE Source Mechanisms

From the observations presented thus far, the authors believe there are three possible sources of AE activity during the gear mesh: tooth resonance, secondary pressure peak in lubricated gears and/or asperity contacts.

Tooth resonance

Estimation of the tooth resonance frequency was accomplished by modelling the gear tooth as cantilever beam and spring mass system. Based on the gear tooth geometry, loading conditions and on the assumption that the load is transmitted along the pitch-line, the tooth resonance frequency was calculated at 75 kHz. This is below the frequency range (100 to 1200 kHz) of the AE sensor employed. In actual gear systems, a lower moment of inertia would be expected resulting in a lower natural frequency than that calculated. This eliminated gear tooth resonance as a source of AE activity during gear mesh.

Secondary pressure peak in the lubricant

The other possible source of AE mechanism in the meshing gears could occur as a result of the pressure distribution between the gear teeth surfaces and the lubricating oil film. This pressure distribution is strongly influenced by the gear operating conditions such as load, speed and material properties, as depicted in figure 2 [9]. From this figure, the occurrence of a local pressure peak far in excess of the Hertzain maximum is observed. This has the effect of reducing the film thickness at the position of the secondary pressure peak. The decrease in film thickness at this particular position can be abrupt, depending on the surface velocity. This sudden increase in pressure or decrease in film thickness could be a source of AE activity although the authors cannot prove this at present. It may be worth noting that load has no influence on the film thickness or level of secondary peak.

If the raise time for the secondary pressure peak is in the order of 0.8 to 10 μs, the secondary pressure peak could generate AE transient burst as observed from the gear mesh AE bursts. This postulation assumes isothermal conditions under pure rolling, however this is not the case within the gear mesh where rolling and sliding are both experienced.

Friction and Asperity Contacts

During the gear mesh; sliding, rolling or a combination of both will occur. As the gear teeth surfaces are limited to manufacturing capabilities (approximately 2 μm) asperity contacts will occur [10] during meshing on almost all gears, particularly as the calculated oil film thickness (approximately 1 μm) in this instance is less than the composite roughness.

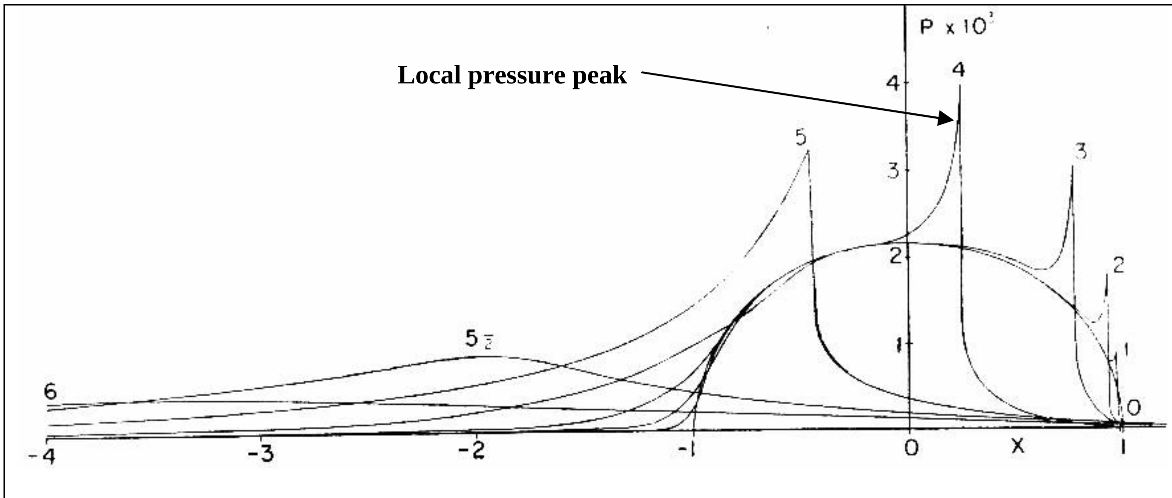

Figure 2 **Pressure distributions for a compressible lubricant with increasing speeds from plots (0) to (5) [9].**

During experiments, Smith [11] noted transient shock pulses during the gear mesh. It was concluded that these shocks were attributed to asperity contact. Whilst a single asperity model was presented as the probable cause of the shocks, the likelihood of such scenario in practice is limited, multiple contacts will be present. However, it was shown that based on asperity width of 5 µm and sliding and rolling velocities of the order of 500 mm/s, the raise time for such a transient event was 10µs. It must be noted that the sensors employed by Smith had a natural frequency of 50 kHz and is outside the range of AE. For this particular investigation, an asperity width of approximately 2µm, with a pitch-line rolling velocity of less than 2000 mm/s, can provide a raise time less than 10µs which will be detected by the AE sensor employed.

As the gear mesh involves rolling and sliding of mating gears it is worth noting that Bones et al [8] suggested that AE activity was most likely due to asperity contact during sliding. In relating AE to sliding friction Dornfeld [12] et al have shown the high sensitivity of AE to sliding speed and applied load. It was noted that the basic mechanism for AE generation was the elastic deformation of the material at asperity contacts. The range of surface finish for the materials investigated was from 1 to 4 µm; comparable with the gears tested in this study. It was noted that the strength of AE amplitude was dependent on surface roughness, in addition to sliding speed and applied load.

The observations of Smith [11], Bones [8] and Dornfeld [12] point to asperity contact as the main source of AE activity for lubricated and dry contacts. As such constant temperature tests were performed by the authors to aid AE source identification during gear meshing. Since the oil temperatures were kept constant, the oil viscosity and film thickness will remain constant during the experiment. It was thought that this may confirm the authors' view that the AE source is due to friction.

The gearbox was run at 745 rpm with a load of 220 Nm for 5 hours at which time the oil temperature stabilised. The gearbox was brought to a stop and adjusted to no-load condition. The gearbox was re-started and run for 10 minutes whilst continuous AE data in the form of r.m.s was recorded at a sampling rate of 100ms over a time constant of 100ms. The gearbox was again brought to a stop and adjusted to the next load condition. Every load condition was run for a 10 minute interval while the continuous AE r.m.s. and energy data were taken. The time taken to strip the rig and set the new torque level was approximately three minutes. During this period the acquisition system was paused. A total of 5 load conditions; 0, 55, 110, 183 and 220 Nm, were tested. In these tests, the temperature of 42.4^{0}C was maintained; ± 1.8^{0}C. A 'Physical Acoustics Corporation' PCI-2 data acquisition system was employed for these tests; pre-amplification 40dB.

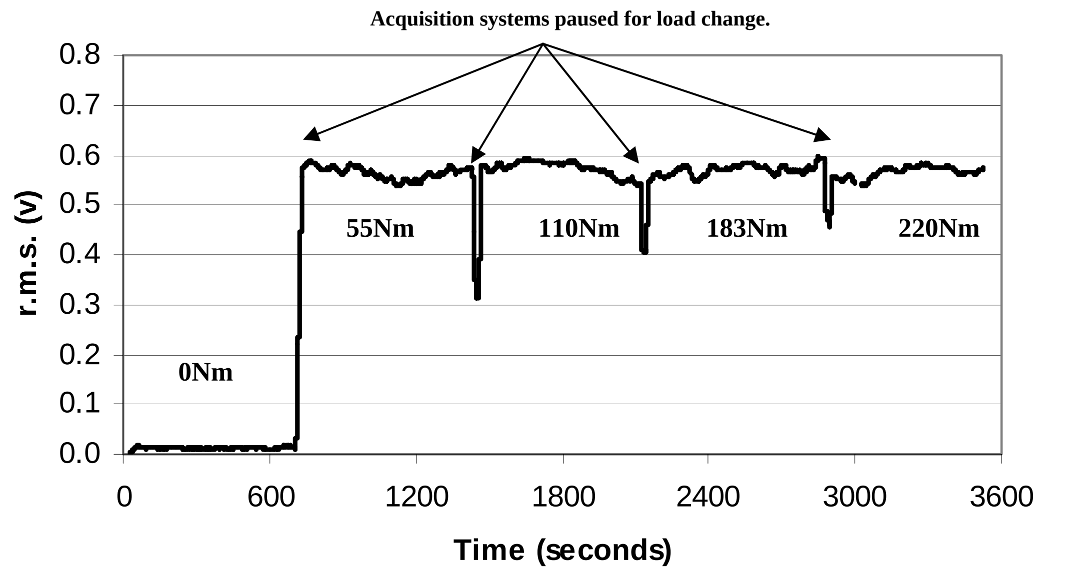

Figure 3 AE r.m.s. remained constant with increased load at 745 rpm.

Following observations presented in figure 3, relatively constant r.m.s. values at a fixed speed and temperature irrespective of load, some resemblance to the phenomena of elastohydrodynamic lubrication for rolling and sliding contact as detailed by Dowson et al [9] is evident. In this particular instance, as the temperature remained relatively constant the effect of sliding friction was assumed constant. As the load had relatively no influence on the level of AE r.m.s it was clear that the source of AE activity was not influenced by the film thickness, pointing towards asperity contact. This is the first known published evidence showing the negligible effect of load under isothermal conditions.

All the above comments provided strong evidence to suggest that the source of AE during gear mesh is attributed to asperity contact. The authors are currently investigating this phenomenon in more detail and results of the study will be subject to future publication.

Conclusion

It is concluded that the source of AE activity at the gear mesh was due to asperity contact. It has been shown that under elastohydrodynamic conditions load has a minimal influence on AE activity. It is postulated that the variation in amplitude of each AE transient burst at the mesh, as evident in figure 1 is attributed to the changing nature of the asperity contact with time, particularly as the individual teeth involve in each mesh are not identical due to the difference in number of teeth between the pinion and wheel.

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