MONITORING OF GAS TURBINE OPERATING PARAMETERS USING ACOUSTIC EMISSION

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ABSTRACT
In this work, Acoustic Emission (AE) sensors were mounted on several parts of a laboratory-scale gas turbine operating under various conditions, the object being to assess the value of AE for in-service condition monitoring. The turbine unit comprised a gas generator (compressor and turbine on a common shaft) and a free-power turbine for power extraction. AE was acquired from several sensor positions on the external surfaces of the equipment over a range of gas generator running speeds. Relationships between parameters derived from the acquired AE signals and the running conditions are discussed. It is shown that the compressor impeller blade passing frequency is discernible in the AE record, allowing shaft speed to be obtained, and presenting a significant blade monitoring opportunity. Further studies permit a trend to be established between the energy contained in the AE signal and the turbine running speed. In order to study the effects of damaged rotor blades a fault was simulated in opposing blades of the free-power turbine and run again under the previous conditions. Also, the effect of an additional AE source, occurring due to abnormal operation in the gas generator area (likely rubbing), is shown to produce deviations from that expected during normal operation. The findings suggest that many aspects of the machine condition can be monitored.

INTRODUCTION
Gas turbines are a versatile, cost-effective source of electricity, mechanical power, and propulsion. However, they also incur relatively high maintenance costs and require frequent in-service inspection. Unscheduled downtime of a turbine can cause vast economic losses and costly time delays. Therefore, the ability to detect abnormalities within turbines, such as blade tip degradation, fouling or fracture, before catastrophic failure occurs is obviously an enormous advantage. Established condition monitoring techniques for turbines generally involve vibration, oil-debris, temperature and pressure monitoring. Whilst these are effective, they are indirect measurement methods which often require significant fault progression before detection is possible. The use of AE to provide earlier detection and classification of rotating and reciprocating machinery faults than the aforementioned conventional techniques has been well documented [1, 2, 3] and there is no reason to believe this will prove any different for turbines. Before such advantages can be realised, however, it is necessary to understand how AE is generated during turbine operation and hence how faults might manifest themselves in AE records.

Armor et al [4] have already reported on the potential use of AE for detection of turbine shaft cracks, blade rubs and bearing deterioration within in-service steam turbines, all of which sources are present in this type of machinery. Sato [5] has proposed a diagnostic system that can detect and distinguish between several different fault types for a steam turbine, including rotor-stator rubbing and bearing faults, from AE acquired at the bearing housings. This was further ratified by Board [6] who applied stress wave analysis (essentially AE analysis) to gas turbine engines and reported that differences in the AE, both in time- and frequency- domains, permitted detection of faults such as in-service seal wear, blade rubbings and induced bearing faults. Bates and Webster [7] detailed a successful application of AE whereby the wear of an abradable seal lining during the ‘run-in’ period of a gas turbine engine for aircraft propulsion was monitored and evaluated. Mba et al have investigated the use of AE for monitoring power generation steam turbines. They verified that a source originating at the shaft-seal tip can be detected by an AE transducer mounted on the bearing housing [8]. They also demonstrated that rubbing can be diagnosed and classified from in-service turbine machinery through AE monitoring [9, 10]. Recently, they have observed a relationship between AE activity and load on a steam turbine unit, and have indicated that a rotor passing through its critical speed can be identified [11].

To date, no published work has related to the use of AE to monitor the combustion and fluid dynamical aspects of turbine operation due principally to the difficulty and impracticability of making observations of faults in large industrial units. In this work we investigate AE acquired from several sensor positions on a vastly smaller scale turbine unit of the order of 4 kW maximum output, although the same combustion, fluid and mechanical principles apply. One aim was to examine if information relating to the normal blade operating conditions, not just abnormal blade rubbing as most previous work has reported, was transmittable through AE. Further aims were to study changes in the AE signature arising from different turbine rotor speeds and from operation with abnormal, induced and non-induced, running conditions.

EXPERIMENTAL APPARATUS

The experimental rig was a laboratory scale Cussons P.9003 two-shaft gas turbine unit comprising a centrifugal compressor and radial turbine on a common shaft, which, together with a propane-fuelled combustion chamber, forms the gas generator. A further radial design, free-power turbine extracts energy from the gas stream and is loaded by a dynamometer which absorbs all power output. The turbine unit is shown in Figure 1 and is illustrated schematically in Figure 2. The AE transducer used throughout these tests was a Physical Acoustics Micro 80D band pass filtered between 0.1 and 1 MHz with data acquired via a CompuScope 512 data acquisition card.

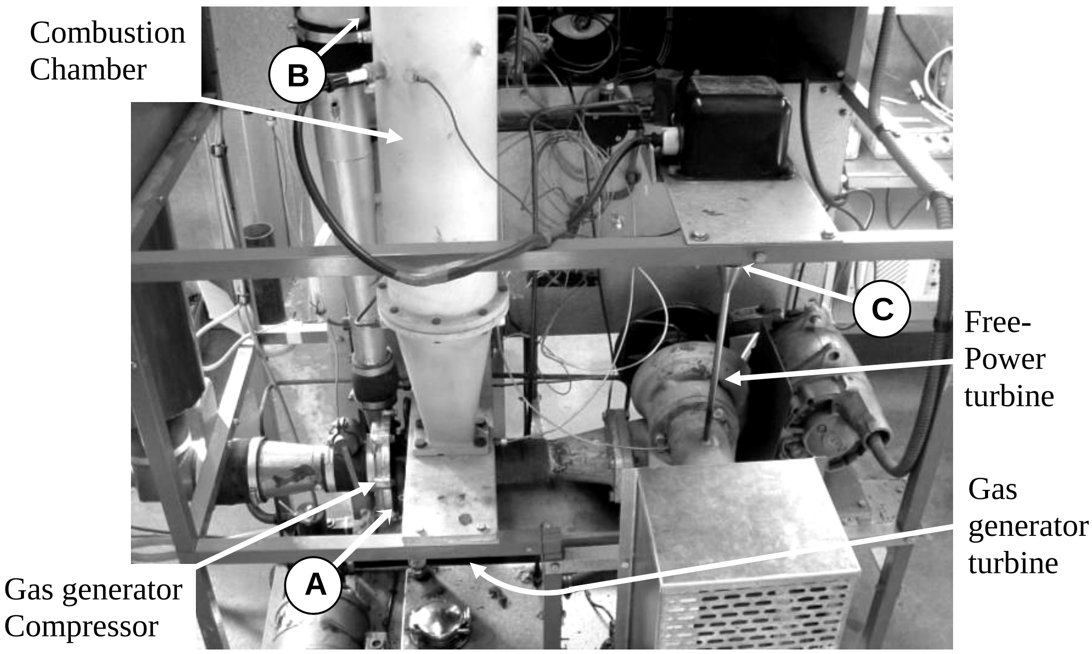

Figure 1: Main features of gas turbine showing sensor positions A, B and C

A test run typically consisted of acquiring data over a range of incrementally increased gas generator shaft speeds, at a sample rate of either 1 or 5 MHz (corresponding to a time period of approximately 0.1 and 0.5 seconds respectively). The limiting factor on maximum attainable gas generator shaft speed was the maximum fuel flow-rate available at a particular time.

To alleviate the problem of long-term degradation of the AE transducer by high-surface temperatures, a waveguide was welded to the exhaust of the free-power turbine. This produced a surface temperature at the sensor mounting plate of the waveguide well under the specified maximum operating temperature of the AE transducer, in this case 177 ^{o}C.

Initial tests were performed using three sensor positions, identified in Figures 1 and 2, with normal operating conditions over a range of operating speeds from 50,000 to 70,000 RPM at the gas generator stage. Other, possibly more revealing, sensor positions, such as the turbine casings and backplates, were discounted due to the high surface temperatures and inadvisability of welding on waveguides. During these initial tests the gas generator shaft was fitted with a sinusoidal Hall-effect timing signal for accurate measurement of shaft speed, and additionally, an estimate of rotational speed could be made via a dial-gauge tachometer. Later tests used only the waveguide sensor position with simultaneous acquisition of a shaft-encoding signal from the free-power turbine which enabled the shaft speed to be accurately determined.

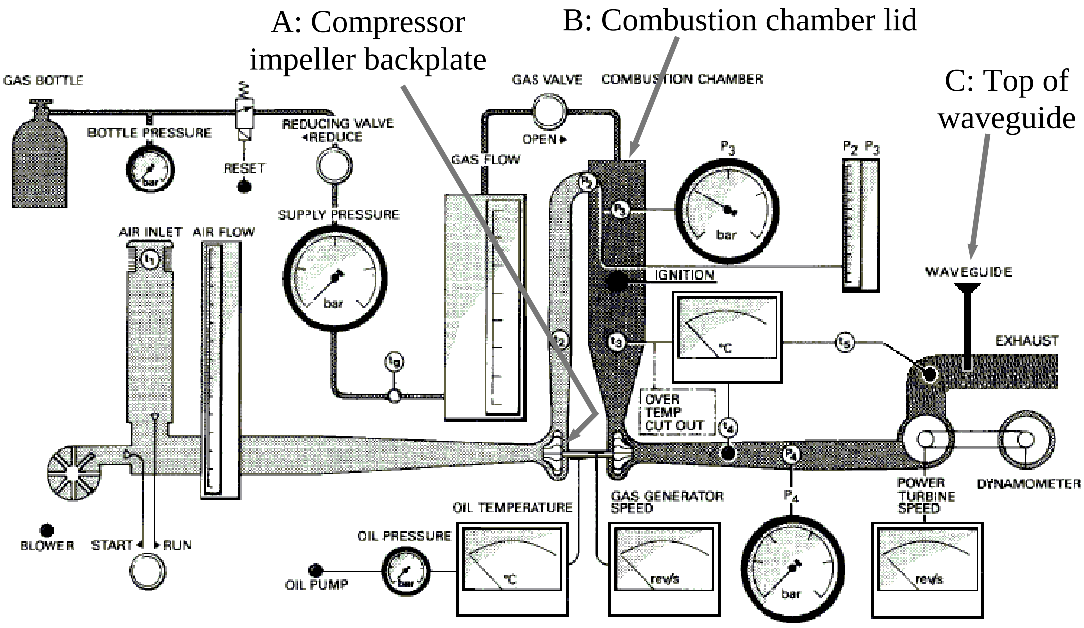

Figure 2: Schematic of turbine showing sensor positions A, B and C.

Blade damage was simulated in two opposing blades of the 10-blade free-power turbine impeller by rounding the sharp corner off first to a radius of 4mm and then running the turbine again under the previous conditions. Thereafter, 4mm incremental increases of the radius were applied, an example of this induced damage being shown in Figure 3. The impeller itself had a maximum diameter of approximately 90mm. The gas generator compressor impeller, shown in Figure 4, was of different construction, consisting of 6 inner and 12 outer blades.

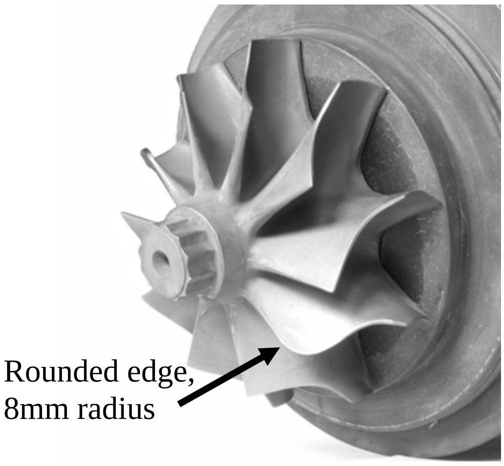

Figure 3: Free-power turbine impeller, damaged blade shown.

Figure 4: Gas generator compressor impeller.

A further fault examined was that of insufficient fuel supply. Here, the fuel supply was lowered beyond that required for idle, at which point the combustion became sporadic and unstable. Any system developed for the purpose of turbine monitoring would require a function whereby this fault could be diagnosed and fuel settings adjusted accordingly.

RESULTS AND ANALYSIS

Over the course of the testing two different types of AE record were observed from the waveguide, sensor position C, and these were:

i) An apparently consistent background noise level (see Figure 5a).
ii) AE consisting of a background level with higher amplitude random pulses (see Figure 5b).

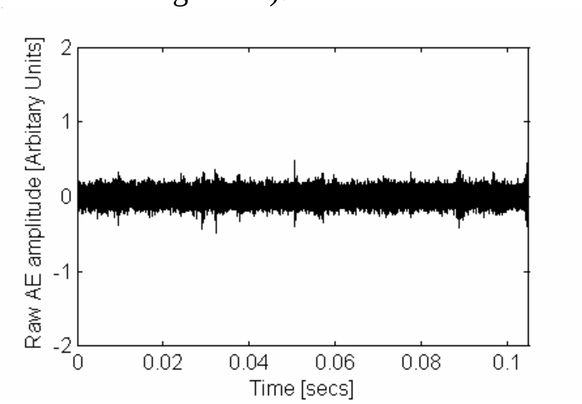

Figure 5a: Consistent background level

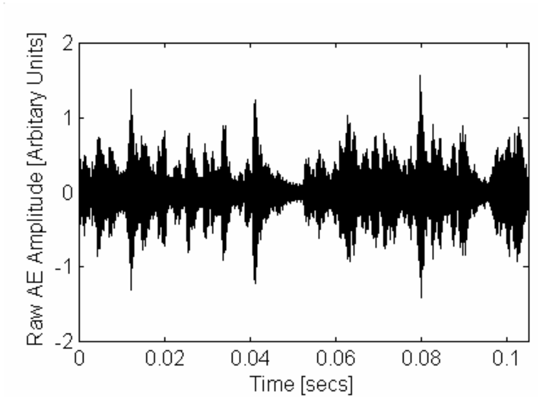

Figure 5b: Additional events

Blade-passing frequency from AE

From the tests where the AE sensor was mounted on the combustion chamber lid, sensor position B, it has been possible to identify the blade passing frequency of the gas generator compressor impeller. Figure 6a shows the spectrum of the timing signal from the compressor/turbine shaft for three different speed settings, estimated at 50,000, 55,000 and 60,000 RPM from the dial-gauge. The actual shaft speeds are slightly less than indicated by the dial-gauge readings but this is inconsequential to this analysis. Focusing in on the modulated region of the spectra from the corresponding AE signals acquired from the combustion chamber lid, see Figure 6b, reveals a peak for each record at around 12 times the shaft speeds identified in Figure 6a. The gas generator compressor impeller consists of 12 outer blades and therefore it is not unreasonable to conclude that the turbulent interaction of the airflow and each of the impeller blades is represented in the AE. This feature was also evident, and somewhat clearer, from data acquired at the backplate of the gas-generator compressor impeller, sensor position A. It should be noted that a plain bearing supports the gas generator common shaft and that the AE records were of the type shown in Figure 5a.

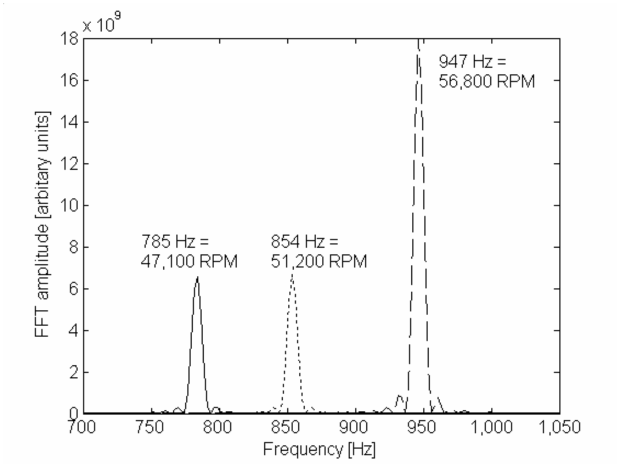

Figure 6a: Frequency spectrum of gas generator shaft timing signal

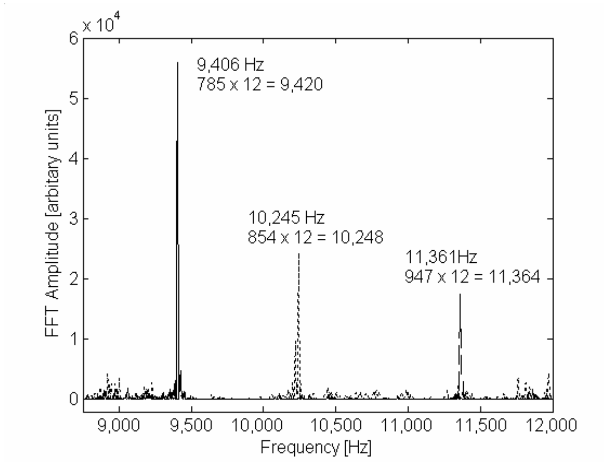

Figure 6b: Corresponding spectrum of AE from combustion chamber lid

Effect of turbine speed on the AE energy

Figure 7 shows the results from 3 separate test runs in which the relationship between free-power turbine shaft speed and AE energy per revolution of the free-power turbine was investigated (the range of gas generator shaft speeds varied from 50,000 to 67,500 RPM). Data were acquired from the waveguide, sensor position C, and were predominately of the type described in Figure 5a, except for a few records which showed isolated bursts of the type seen in Figure 5b. These occasional events account for the outlying points seen in Figure 7 and also a few additional points that are not shown in Figure 7 up to a value of 150.

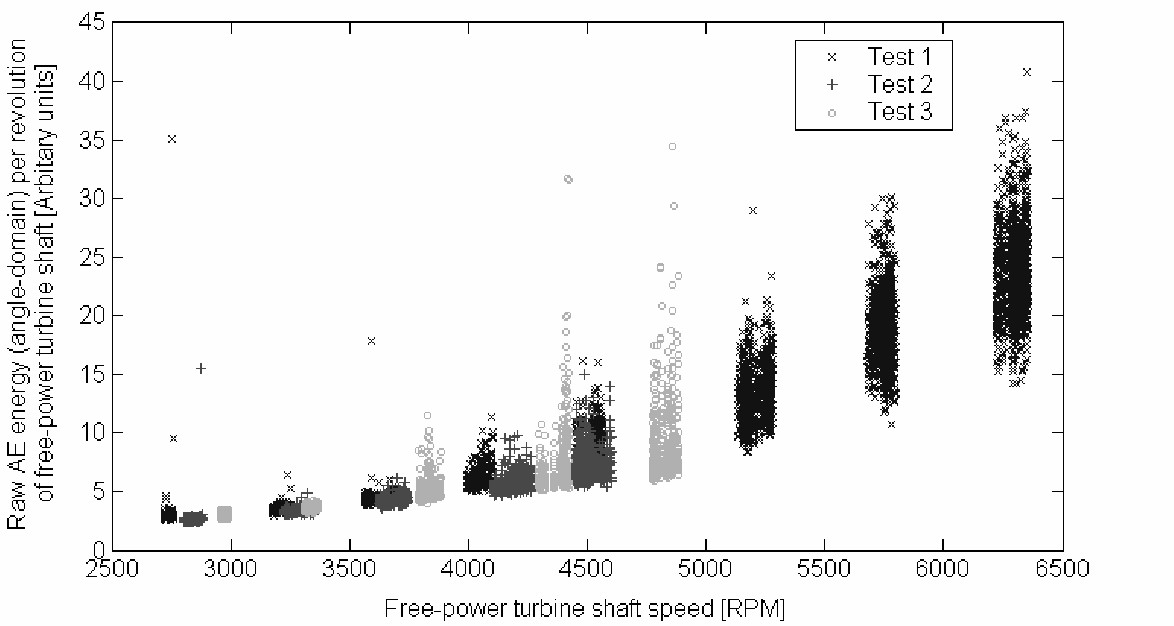

Figure 7: Increasing AE energy content with increasing shaft speed

It is clear that there is a relationship between the shaft speed/power output and the AE energy per revolution of the free power turbine shaft. A similar relationship could have been constructed with the energy per revolution of the gas generator shaft since, in these tests, the free-power turbine speed was dependent upon the gas generator shaft speed. Indeed, the background AE energy may be attributable to a number of sources from both turbines, notably fluid flow; exhaust gas and blade turbulence, and also bearing-related sources. All these mechanical or fluid events would be expected to increase in intensity with increasing speed/power output of the turbine unit and hence the trend seen in Figure 6 for the background type AE records can be considered to be that produced by normal operation of the turbine unit.

The results of a further test, test 4, are shown in Figure 8 together with the results previously given in Figure 7, for tests 1, 2 and 3. The data in this case is presented as AE energy in the time-domain per revolution of gas generator shaft against estimated gas generator speed. During this test, an audible noise was heard to originate from the gas generator area and the AE acquired was of the nature exhibited in Figure 5b. The results indicate a similar trend to that established in Figure 7 but with increased AE energy levels. The precise mechanical or fluid origin of this increased AE is unknown at present, but is almost certainly related to the audible noise from the gas generator area and indicative of rubbing, either within the bearing or between the turbine or compressor impellers and their respective housings.

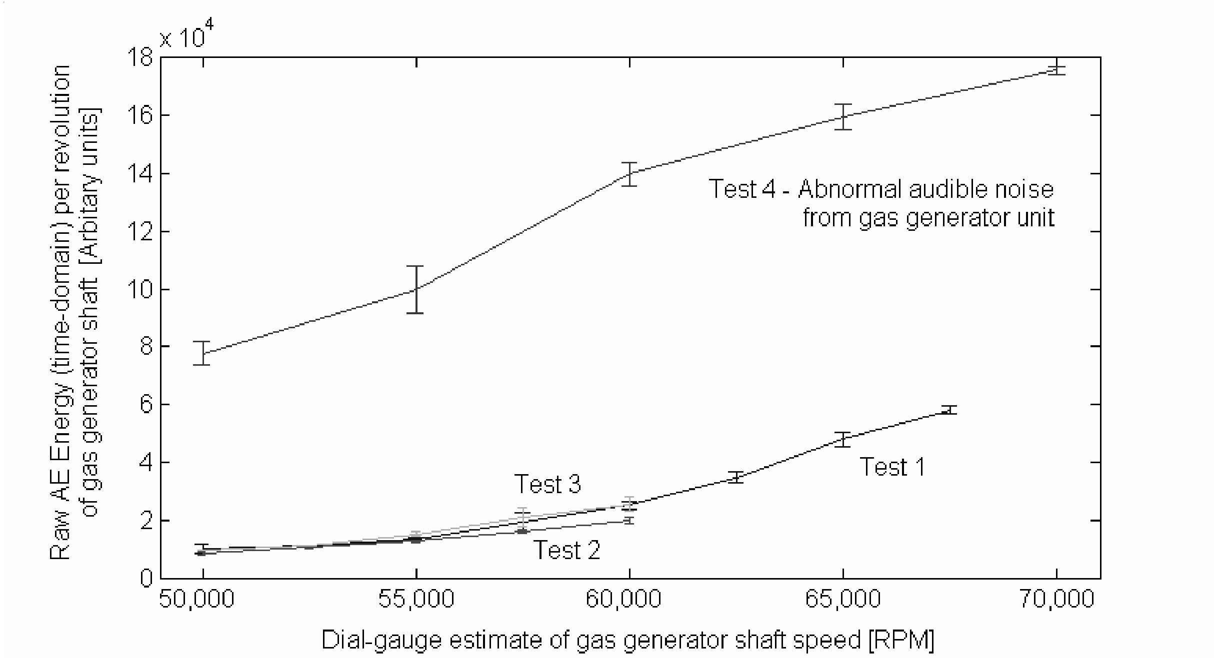

Figure 8: Effect of further AE source from gas generator turbine unit, indicative of abnormal running conditions

Detection of damaged blades in free-power turbine

Blade tip degradation was simulated by applying a radius to the originally sharp edges of two opposing blades of the free-power turbine impeller (see Figure 3a). The results of running the turbine over a range of gas generator speeds where 8 and 12 mm radii were applied are shown in Figure 9, AE observed during these tests being of the type described in Figure 5a. The reduced levels of AE energy associated with the larger fault radius may be due to the fact that with a larger gas-leakage area, i.e. the 12mm radius, the gas-leakage velocities, assuming a constant flow-rate, will be reduced and hence less AE generated.

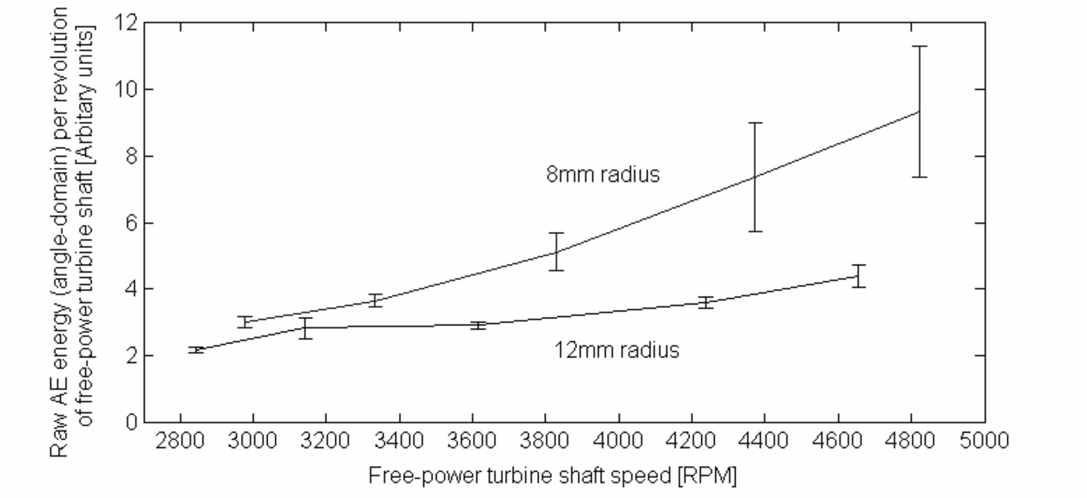

Figure 9: Effect of simulated damage to blades of free-power turbine

Insufficient fuel supply / Unstable running

Figure 10 shows AE acquired from the backplate of the gas generator compressor during a period of sporadic, unstable running, i.e. the fuel supply was reduced to below that required for consistent idling. The increased AE levels and character of the events are indicative of impact-type events which are most likely due to shock forces transmitted to the gas generator turbine unit through the reverberations caused by the on/off nature of the combustion.

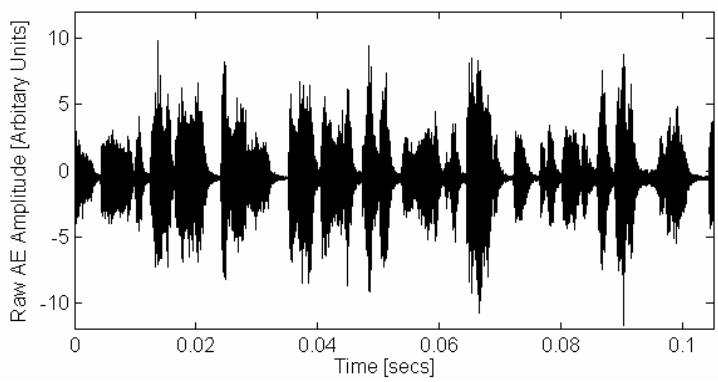

Figure 10: Insufficient fuel supply / unstable running

CONCLUSIONS

This work is at a preliminary stage, but has demonstrated that the operating parameters of a laboratory-scale turbine unit can be monitored by AE. The identification of the gas generator compressor blade-passing frequency via AE represents a significant monitoring opportunity. Deviations from the expected frequency or a dispersion of the frequency over a wider band may be an indication of individual blade malfunction. More revealing AE regarding the turbine impellers is potentially available from the external surfaces of the turbine casings and backplates, although a means needs to be found to interrogate these hot surfaces without damaging the sensor.

Data acquired from the waveguide permitted a trend to be identified whereby the turbine running speed is represented in the energy content of the background AE. Moreover, the presence of abnormal operation of the gas generator turbine unit is readily distinguishable in the AE from that of normal operation. The effects of two degrees of induced fault within the free-power turbine have also been shown.

Recent efforts by other authors have verified that similar characteristics to that found in this work are also evident on full-scale power-generation turbines. Hence the results presented here, particularly the new findings regarding blade-passing frequency, have the potential to be scaled up to full size turbine units. Furthermore, this illustrates that a laboratory scale turbine unit, where operating conditions are easily altered and simulated faults more readily introduced, has the capability to assist in the development of an AE-based condition monitoring system for power-generation and propulsion turbines.

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