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EXPERIMENTAL INVESTIGATION AND ASSESSMENT OF COMBUSTION INSTABILITY AND ENGINE VIBRATIONS; AS AN IMPACT OF USING NOVEL ALTERNATIVE FUELS WITH LOW AROMATICS IN A GAS TURBINE ENGINE

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ABSTRACT

This investigation centres upon the investigation of vibrations characteristics of a low aromatic HEFA fuel when compared to standard Jet A1. Both the pure HEFA fuel and pure Jet A1 were tested as well as 10 blends of different percentages of the two fuels were tested. The experiments were conducted on a small gas turbine engine at the Low Carbon Combustion Centre of the University of Sheffield. The vibrational analysis suggests that aromatic compounds in the fuel composition may affect the instability characteristics of a given fuel. It was found that the pure alternative fuel has markedly higher vibrations when compared to blends of the alternative with Jet A1 and pure Jet A1 as well. This relationship was not proportional in the blends. Suggesting that a particular compound in the Jet A1 has a disproportionate impact on increased combustion stability.

INTRODUCTION

As the drive towards reducing carbon emissions intensifies both due to public perception and legislative motivations, cleaner lower polluting fuels are destined to play a major role in the short to medium term, as other more wholly renewable fuels begin to mature (Blakey, Rye and Wilson, 2011). To this end it is of critical significance that these new alternative fuels are subjected to methodical testing in their destined applications; in this case Jet fuel for gas turbines. As it stands the lion's share of research being done on the performance of alternative fuels pertains to the fuels emissions when burnt in gas turbines (Kugele, Jelinek and Gaffal, 2005; Khandelwal, Wijesinghe and Sriraman, 2018; Zheng *et al.*, 2018). And therefore, very little research is being done on the vibrations and noise characteristics of the engine when it is running on alternative fuels the current research that has been done is not remains non-comprehensive (Khandelwal, Roy and Lord, 2014; Wijesinghe and Khandelwal, 2019).

Combustion instabilities are defined by Lieuwen and Yang "large amplitude oscillations of one or more natural acoustic modes of a combustor" (Lieuwen and Yang, 2006). They further go on to state that combustion instabilities tend to transpire at the natural frequencies of the combustor in question. It should be noted that currently the main method by which combustion instabilities are combated are by designing the combustion chamber and associated parts so that the natural frequencies of the combustors are well outside the reach of the flames heat release oscillations. When considering the implementation of a myriad of new alternative fuels it is not practical to design an engine to suit each and every fuel. To this end there exists a need to determine how the composition of a given fuel tends to behave from an instability perspective when burned in a conventional gas turbine designed to burn the current fossil-based aviation fuel Jet A1. Lang et al have conducted a comprehensive investigation on the subject of actively designing combustors and engine packages to combat both instability and noise by deveining combustors with natural frequencies outside the commonly known combustion instability frequency ranges (Lang, Poinsot and Candel, 1987).

Further investigations into the visualisation of combustion instability has been conducted by Candel using spark-schlieren photography which goes on to depict the mechanisms of combustion instability as well as determining their origin points such as the turbulent vortices originating from the injection ports etc. They go on to describe that in conventional combustor design that high frequency pressure oscillations in the combustor can be damped by passive methods which involves adding baffles, resonators and acoustic liners etc. however they mention that these physical modifications are of limited utility when trying to combat low frequency. To combat these low frequency oscillations the fuel pumping system must be modified to alter the fuel injection distribution or even in worst case scenarios even restricting the flight envelope of the aircraft and hence the combustor operational environment (Candel, 1992).

The means by which combustion generates instabilities in

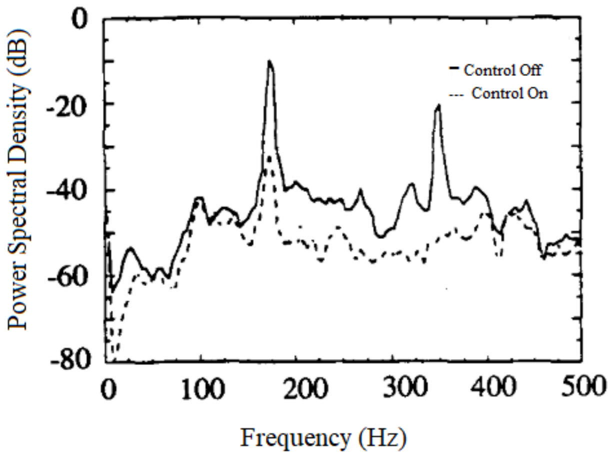

Figure 1 Noise emitted by combustors with no active control and with active control (Candel,1992)

the acoustic modes of a system are described by the Raleigh's criterion. Which states that an intervallic heat transfer system adds energy into the acoustic domain if the heat is added or removed from the gas whilst its pressure is above or below its average (Lieuwen and Yang, 2006). This process in general describes the circumstances during which unstable heat release from combustion adds energy to the acoustic field. However even though energy is released into the acoustic field does not particularly results in instabilities. Instabilities only spontaneously results from combustion when the pace at which the energy is provided to the acoustic field is greater than the pace at which this energy can be dissipated in the form of noise or perhaps transmitted through throughout the combustor.

Furthermore, it should be noted that as the demand for ever more increasing fuel efficiency and combustion efficiency is required the gas turbines of today are required to burn leaner and leaner increasing their AFR (Air-Fuel Ratio) (Blazowski, 1977). As the AFR increases the turbines run closer and closer to their Lean Blow out (LBO) limits. When nearing this point the propensity for combustion instabilities are greatly increased. Moreover operating with these instabilities lowers the performance of combustors as well as reducing their service life (Lieuwen *et al.*, 1999).

Moreover combustion instabilities if left unabated tends to generate increased wear and tear of mechanical components and even catastrophic failure of components in the most severe cases ('Combustion Instability And Its Passive Control: Rolls-Royce Aeroderivative Engine Experience', 2006; Bykovskii, Vedernikov and Polozov, 2006; Goy, James and Rea, 2006; Krebs *et al.*, 2006; Janus *et al.*, 2014). In general combustion instabilities are affected by several factors, first and foremost begin the combustor design and packaging secondly the fuel flow rate and the injector design which is affected by the spray pattern of the fuel in question as well as the droplet size and distribution (Candel, 1992; Vignat *et al.*, 2018). It is at this point where alternative fuels can make a superficial impact upon instabilities.in that the fuel flow rate and the spray

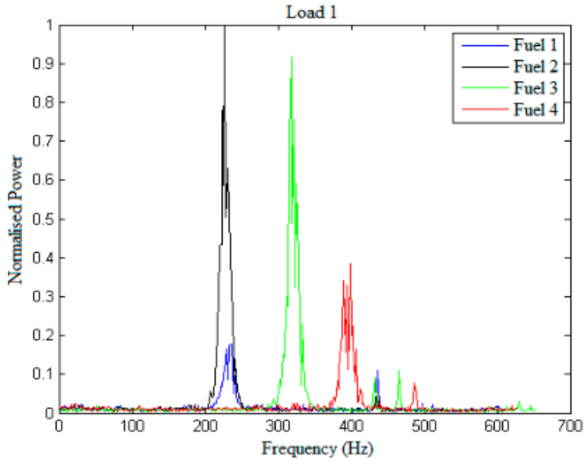

Figure 2 PSD comparison between several fuels under one condition (Khandelwal, Roy and Lord, 2014)

patterns are dependent upon bulk fuel properties such as density and viscosity as well as intensive properties such as chemical composition and carbon to hydrogen ratio. As these properties tend to differ for each fuel it bears investigating the impact of fuel properties on how combustion instabilities propagate.

It has been found that the vibrations and noises that are generated by combustors fall into three distinct frequency bands. These are namely low (sub 50Hz) intermediate (between 50Hz and 1000Hz) and finally high frequency (above 1000Hz) (Khandelwal, Wijesinghe and Sriraman, 2018). In this investigation the great focus is upon the intermediate range vibrations due to the ease of acquiring the data in this range without much clutter and noise.

Some prior work conducted by Khandelwal et al. regarding the performance of various alternative fuels suggest that the main peaks generated by each fuel remain relatively similar however with higher or lower peak amplitude and more interesting a phase shift as can be seen from the above figure regarding fuel 2 and fuel 3.

Therefore, the aim of this particular investigation is to determine the exact effect of alternative fuels on noise and vibrations of a gas turbine. As this would greatly impact the knowledge and ability to gear future alternative fuels to be developed with the aim of being true drop-in alternative fuels.

METHODOLOGY

The experiment was conducted using a Honeywell GTCP 85 type Auxiliary Power Unit (APU). The alternative fuel as well as a reference Jet A1 and several blends composed of the two fuels were run on the APU at 3 different engine conditions. These were as follows;

- No Load (NL) condition which equates to roughly engine idle.
- Environmental Control system start (ECS) which equates to approximately 50 % engine power. This condition would be used in operation circumstances

while the aircraft is on the ground and cabin electrics and air-conditioning is activated.

- Main Engine Start (MES) the final setting which equates to the engines full power rating, used in operational situations to provide bleed air to start up the main engines of the aircraft.

During the experiment the engine was first warmed up to MES then stepped down to ECS and them finally to NL condition to ensure that the engine was stable on the given fuel blend and would produce stable results. The APU condition details are as follows;

Table 1 APU settings description

Parameter	APU Operating Conditions		
	NL	ECS	MES
Fuel Flow Rate (g/s)	17.7 ± 0.2	25.8 ± 0.3	31.1 ± 1.1
Turbine Speed (RPM)	41435 ± 127	40828 ± 318	40191 ± 742
Air/Fuel Ratio (AFR)	135 ± 3.9	84.4 ± 0.8	62.2 ± 1.0
Exhaust Gas Temperature (°C)	324.1 ± 6.0	475.2 ± 5	600.0 ± 7.6

The alternative fuel used in this investigation was derived from a Hydropocessed Esters and Fatty Acids (HEFA) bio fuel. The fuel properties of such as density are listed in table 2. The fuel was then blended by volume into several proportions as can be seen in the results section.

Table 2From table2 it can be seen that the density of the alternative fuel is around $40kgm^{-3}$ less than that of the baseline jet A1. This also makes the fuel outside the limits prescribed by the fuel standard ASTM D 1655 by around $20kgm^{-3}$. This may impact the behaviour of the fuel when burned. Moreover, the percentage of aromatic compounds in the alternative fuel is markedly lower when compared to the baseline fuel . this make the alternative fuel less polluting in terms of particulate matter. It is well known in the literature that particulates emitted by engines are directly proportional to amount of aromatics in the fuel (Corporan *et al.*, 2007; Dewitt *et al.*, 2008; Moore *et al.*, 2017; Khandelwal, Wijesinghe and Sriraman, 2018). However, it has also been noted that aromatic compounds are required in the fuel to aid in the lubricity and seal capability of the fuel. Without which seals in the entire fuel system are affected due to contraction which can then lead to leaks (Corporan *et al.*, 2011).

Table 2 Fuel properties

Property	Allowable Range	Jet A-1	Method	HEFA	Method
Density at 15°C, kg/m^3	780 - 820	802	ASTM D4052	759.9	ASTM D4052
Distillation temperature, °C					
10% boiling point	155 - 201	164.1	IP 123	169.6	ASTM D86
Final boiling point	235 - 285	254.2	IP 123	243.9	ASTM D86
Composition					
Aromatics, volume %	15 - 23	18.2	ASTM D1319	1.4	ASTM D2425

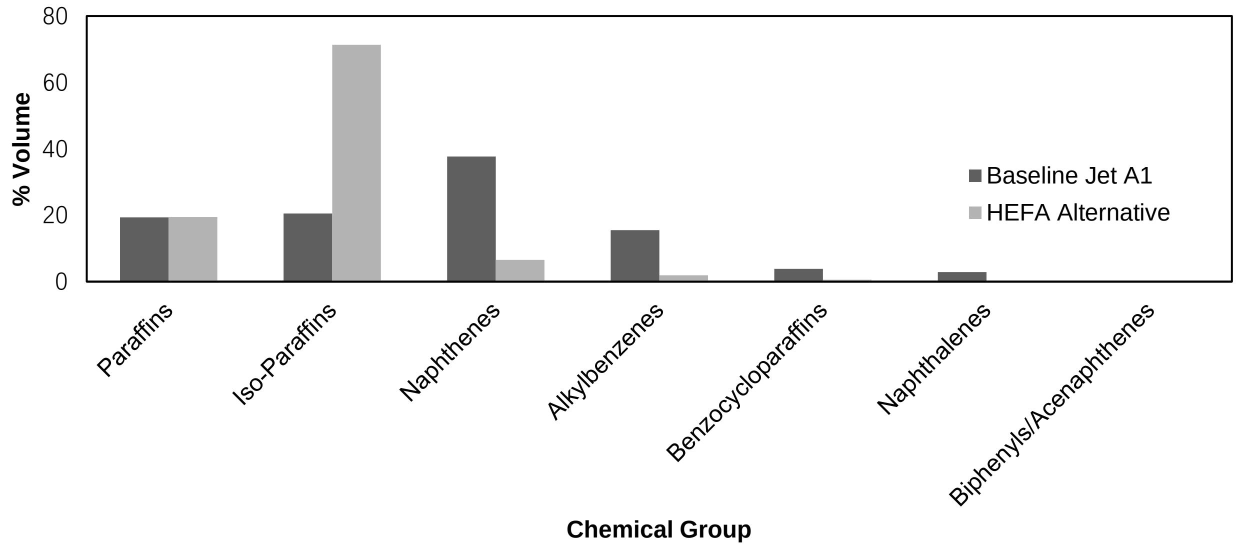

Figure 3 Gas Chromatography data of the two fuels

Figure 3 shows the Gas Chromatography (GC) data for the 2 fuels. As can be seen the amount of Naphthenes, Alkylbenzenes and Naphthalenes is drastically lower for the alternative HEFA fuel when compared to the alternative Jet A1 fuel. The HEFA makes up for this lack of aromatic compounds by volume with addition of extra iso-paraffins, which make up around 70% of the HEFA fuel by volume. The experiments were conducted using 2 accelerometers affixed to the frame of the APU measuring perpendicularly to the axis of the APU. These devices are able to measure the vibrations in the surfaces they are attached to in the form of acceleration (ms^{-2}). The data was acquired using WINDAQ and processed using MATLAB (Filtering, anti-aliasing etc). the sampling frequency used was 2kHz which gives a usable Nyquist frequency of 1kHz. As it is well known that in general combustion instabilities occur at relatively low frequencies this should not pose a problem.

RESULTS AND DISCUSSION

Figure 4 shows the frequancy domain data for the pure alternative fuel vs the pure baseline fuel. It is immediately visible from the figure that there appears 2 extremly sharp peaks at approximately 50 and 950 hz. These correspond to mechanical rotaional components within the engine mainly the fuel pump, compressor/turbine oil pump etc. even though these rotaional components are not directly impacted upon by combustion instabilies occuring in the cannistor, audibly it could be heard the engine was running rougher when on the pure HEFA blend. This is refelcted by the fact that the peak amplitudes for Jet A1 are far lower compared to the HEFA fuel in Figure 4. This can be explained by perhaps the turbine experieencing pressure fluctions inside the engine moreso than normal due to the unconventiional fuel being used. The turbnie which starts to vibrate transmits these forces alogn the shaft and onto the compressors and other mechanicanically driven components from the shaft. Furthermore it can be seen from figure 4 that the fft is symetrical this is normal as this is a mathematical property of a DFT.

Figure shows a filtered version of the pure blend Fast Fourier Transform (FFT) to exclude the two peaks discussed previously and portrayed in Figure 4. Again, it is clearly visible that the pure alternative fuel at all frequencies has a higher amplitude when compared with the pure baseline fuel. Clearly lending credence to the fact that at the full power MES condition the alternative fuel performs poorly in terms of vibrations. Moreover, the plots remain identical in terms of the locations of peaks i.e. peaks present in the alternative fuel FFT is mirrored in the baseline Jet A1 FFT however with a lower amplitude. This lends credence to the accuracy of the data in terms of acquisition and sensor shift. As if the sensor positions shifted between test there would at least be some phase difference between the peak frequencies.

Figure goes on to show the FFT data for 6 different blends of HEFA alternative fuel and JET A1. Again, it is visible that there is a trend where the more alternative fuel is present in the blends the more vibrations are present. With the 95% HEFA blend performing the worst and the 5% HEFA

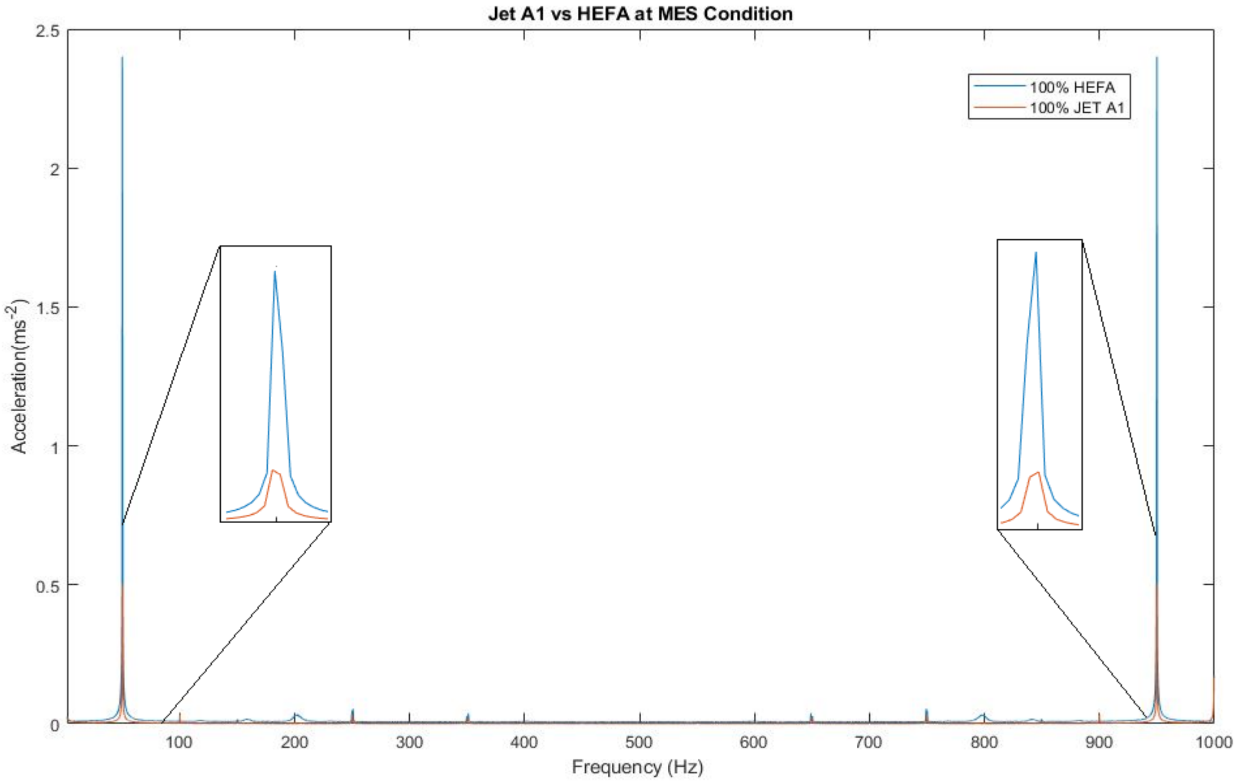

Figure 4 Jet A1 vs HEFA fuel pure blends at MES condition Frequency data

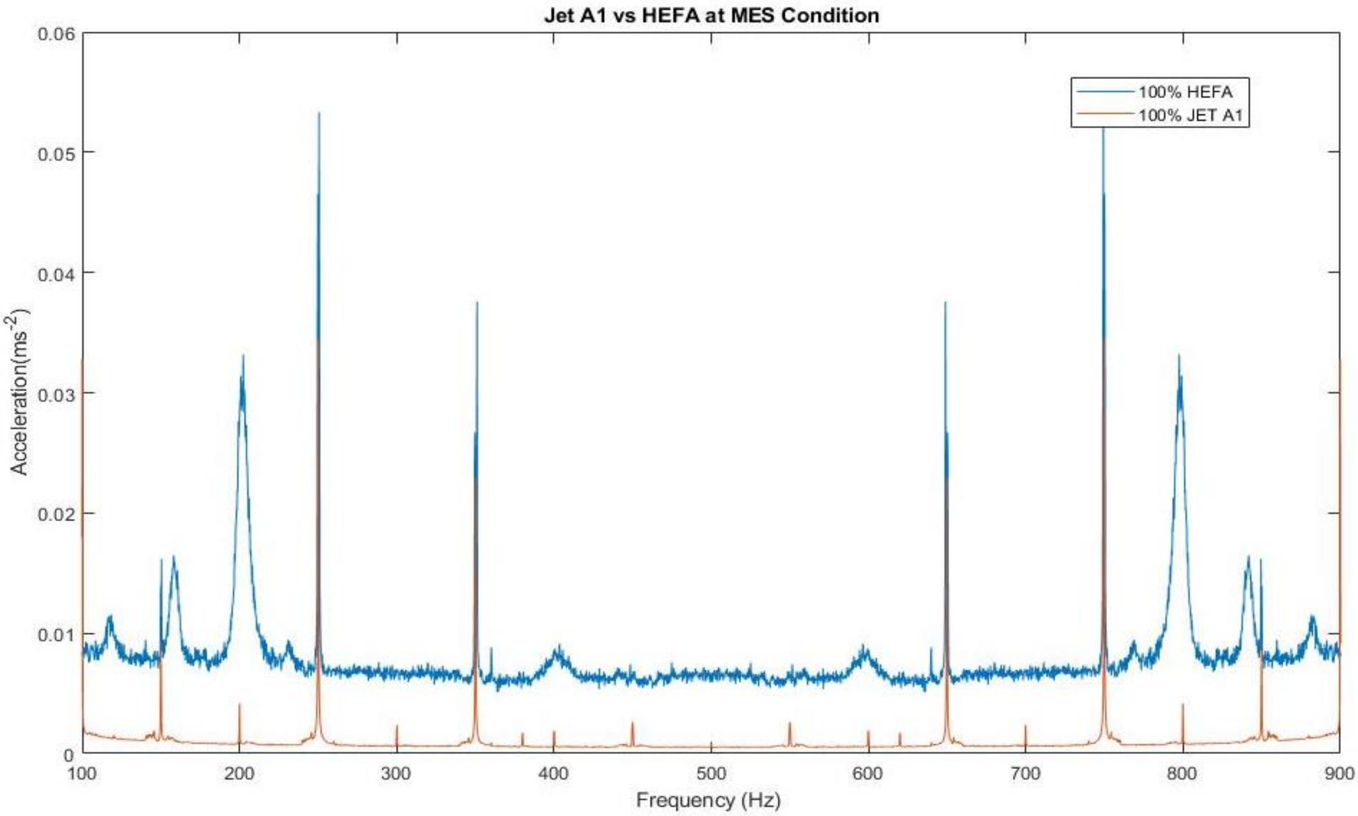

Figure 5 Filtered pure blend frequency data between 100-900hz

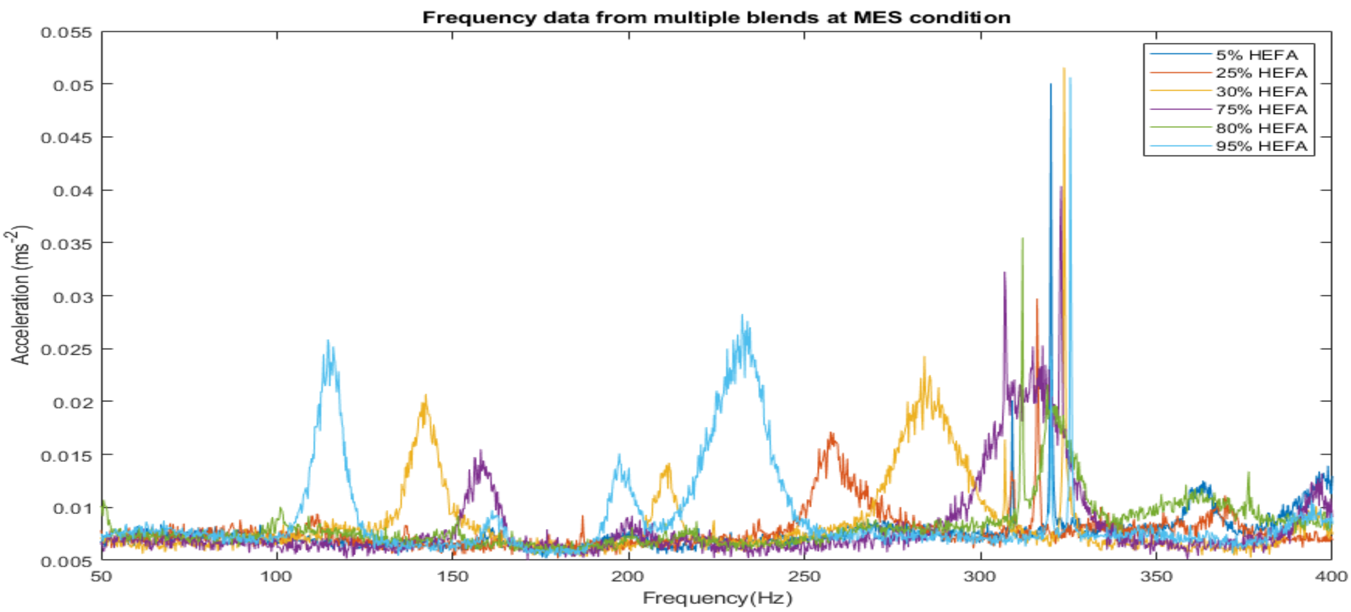

Figure 6 FFT data for the different blends

blend performing the best in class. A notable anomaly in the results being the 30% HEFA blend. Moreover, the figure is low pass filtered to 400Hz so the large mechanical peaks from the previous figures do not distort the data. So here we can see some phase shifts between the peaks at 100-300 Hz whereas the percentage of HEFA increases the peaks become smaller and moreover are shifted to higher frequency limits (i.e. the peaks for 95% HEFA at 100Hz has been shifted to 150Hz for the 75% HEFA blend.

Figure and 8 goes on to show the root mean square data (RMS) for both accelerometers at all 3 conditions with varying percentages of Jet A1. The two figures show almost statistically insignificant trends in terms of RMS amplitude with perhaps the exception of the pure biofuel blend (0%jet A1 which appears to have an extortionately high RMS compared to all the other blends. Normally this may be

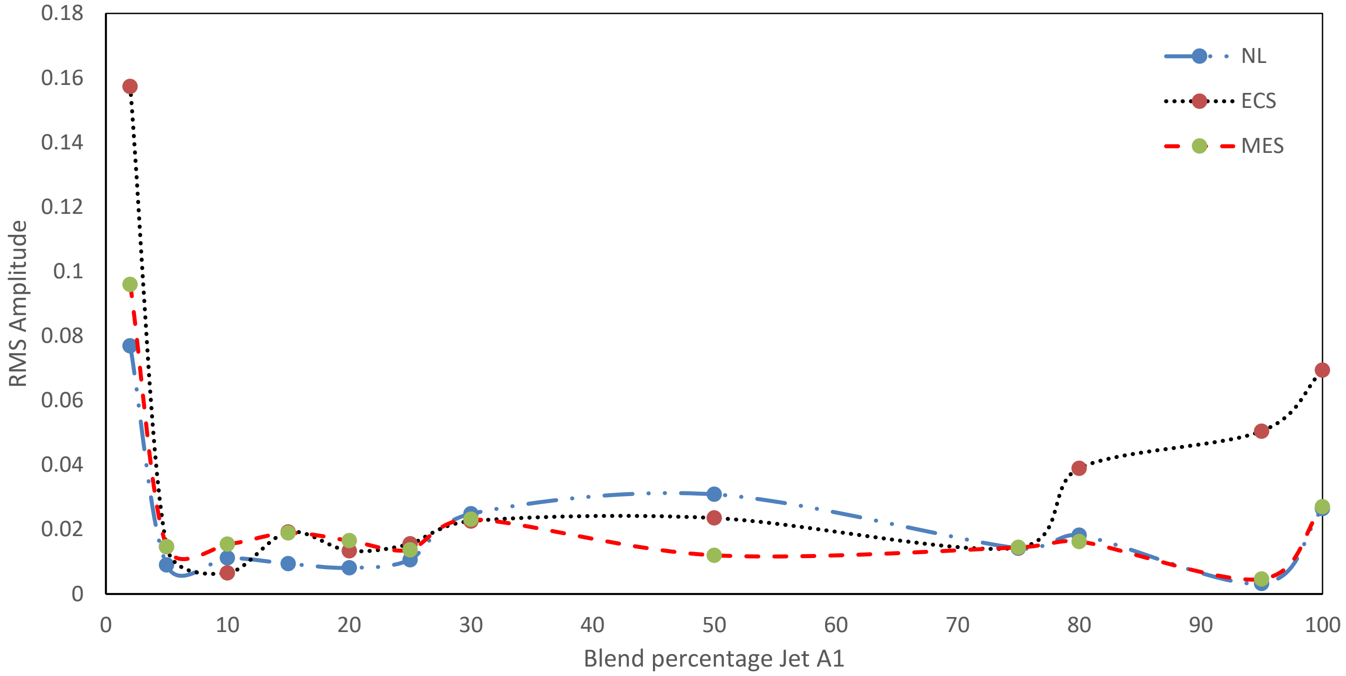

Figure 7 RMS data for all blends on accelerometer 1 at all 3 conditions

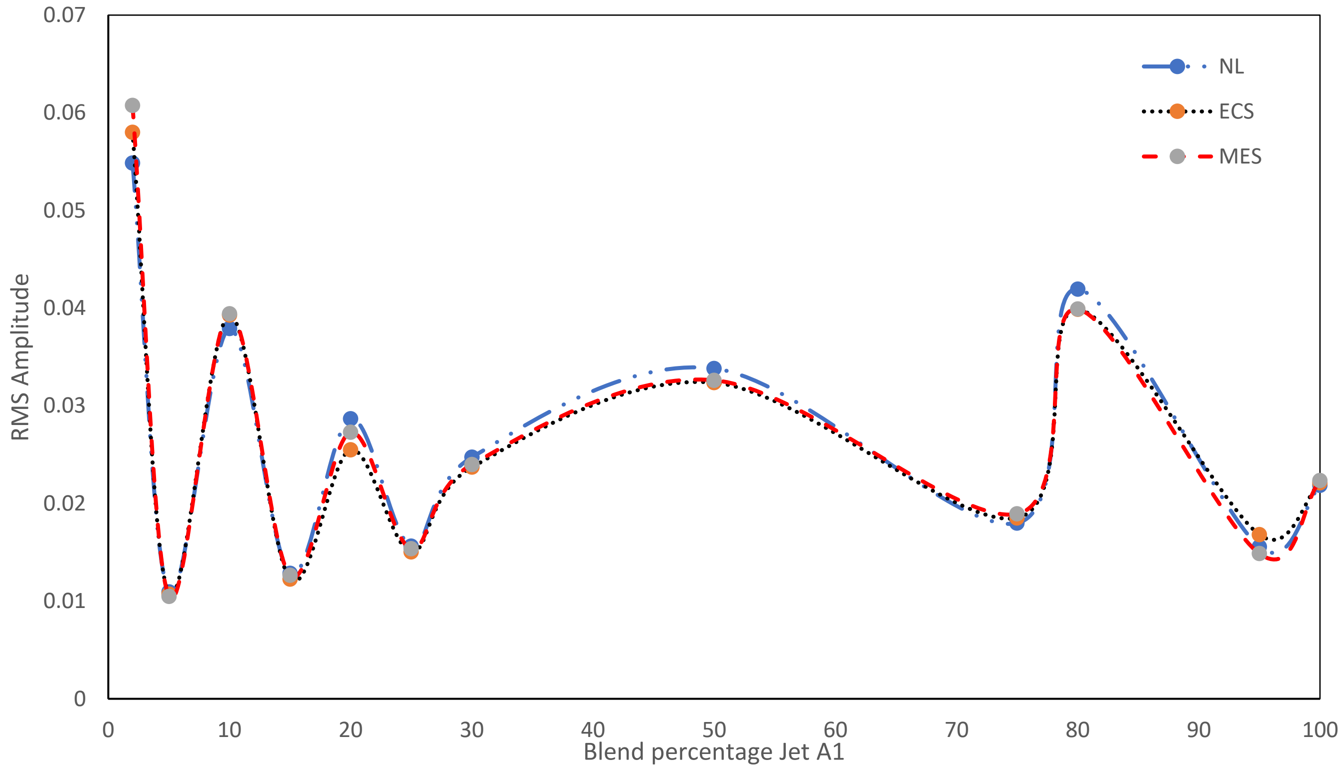

Figure 8 RMS data for all blends on accelerometer 2 at all 3 conditions

considered an anomaly however this phenomenon is present in all conditions across both accelerometers. Also, the pattern in the RMS data suggest that there is systematic phenomenon going in the vibrations as the pattern is repeated exactly for all 3 conditions for both accelerometers. The pattern however changes between accelerometers.

Further of note is the fact that in all the conditions in figure the RMS value for the pure alternative fuel without blending has a markedly higher RMS value. Suggesting that a particular compound in the Jet A1 and the mixed blends tends to have a disproportionate impact upon the vibrations generated by the engine.

CONCLUSIONS

In conclusion it can be seen that the fuel composition has an impact upon the noise and vibrations characteristics of the engine. It remains to be seen whether this is due to the aromatic compounds as a whole or a particular compound only. This can be investigated further by burning only single types of aromatics in future fuel blends. moreover, as the major difference between the HEFA and the pure Jet A1 is the dearth of aromatic compounds in the alternative fuel, it may be inferred that aromatic compounds have an effect upon the noise and vibrations characteristics of the engine.

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