EARLY DETECTION OF CRACKS IN REAR SUSPENSION BEAM WITH THE USE OF TIME DOMAIN ESTIMATES OF VIBRATION DURING THE FATIGUE TESTING

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Summary

In this article an early crack detection method during fatigue testing has been described. The test object was a beam mounted on a durability test bench. Piezoelectric accelerometers were mounted onto the beam. With observation of the signals from the accelerometers it was determined what change of the signal was caused by crack appearance during the test. Three car beams were tested. The measurement method and testing bench are described in this work.

To determine the change of the signal and show potential cracks, time domain estimates have been used: RMS, peak, peak-peak, Crest Factor and Kurtosis. Results for all these estimates are listed in tables. Conclusions were drawn according to their variations in particular time ranges.

Keywords: crack beam, diagnostics, vibroacoustics, fatigue tests

BADANIE WCZESNEGO WYKRYWANIA PĘKNIĘĆ W BELCE ZAWIESZENIA TYLNEGO Z WYKORZYSTANIEM ESTYMAT PRZEBIEGU CZASOWEGO WIBRACJI PODCZAS PRÓBY ZMĘCZENIOWEJ

Streszczenie

W pracy opisano metodę wczesnego wykrywania pęknięć podczas prowadzenia testów zmęczeniowych. Badanym elementem była belka samochodowa zamontowana na stanowisku do testów wytrzymałościowych. Na belce zamontowano piezoelektryczne czujniki drgań. Na podstawie obserwacji sygnałów z czujników drgań określono jaką zmianę w sygnale powoduje pojawienie się pęknięcia w badanym teście wytrzymałościowym. Przebadano trzy belki samochodowe. Opisano sposób wykonania pomiarów oraz wykorzystane stanowisko badawcze.

Do określenia zmian i pokazania potencjalnych pęknięć posłużono się estymatami wyznaczonymi z analizy czasowej: RMS, pik, pik-pik, Crest Factor oraz Kurtoza. Wyniki tych estymat, dla poszczególnych belek, przedstawiono w tabelach. Wnioski przedstawiono na podstawie zmian ich wartości w poszczególnych zakresach czasowych.

Słowa kluczowe: pęknięcia belki, diagnostyka, wibroakustyka, testy zmęczeniowe

INTRODUCTION

Safety is the one of main elements that the automotive industry has great emphasis on for many years. This results in many tests that vehicle or component manufacturers have to perform in order to assure quality, both in the design phase and in conformity of production.

Competitiveness causes the necessity of cheaper technologies, which often leads to simplification of technological processes to lower the price, or, on the contrary, creating very sophisticated processes that give the chance of material reduction which also affects in lowering the price. That kind of actions have to be controlled by research that ensure the product still meets safety restrictions.

According to active safety, suspension elements are one of the most important. These elements are being tested all the time in checks on both the material and the production processes. There are many technological processes that can slightly influence the endurance of the material by structural modification (welding), changes of the roughness (grinding, machining), etc. In the case of a lack of control, in that kind of suspension element there might come into being a crack, even during vehicle operation, which remains undiscovered while still increasing in length.

To avoid those kind of situations, durability research is performed, more precisely named fatigue tests. The aim of this kind of testing is to estimate the duration of endurance (measured in cycles) and to define possible defects in the test objects, based on cracks or other defects arising during the test. It is obvious that control of objects to detect individual cracks at an early phase is necessary. It is often realized by visual inspection, which is very cumbersome. That is why there is research and development into new methods of detecting cracks. Vibroacoustic signal analysis is well suited to this task.

There were many pieces of research on detecting cracks using modal analysis or related methods [1, 2, 10]. These methods are excellent to study simple objects that are vibrating freely (like a beam restrained on one side) and huge real structures like bridges, buildings or airplane wings.

Another crack detection method that many articles describe is the Acoustic Emission method (AE) [6, 7, 8]. This method allows detection of even micro cracks if the transducer's frequency range covers the frequency of the acoustic wave emitted during the formation of the crack. This method is good in materials where the sound propagation speed is low. In steel and similar materials, due to the high speed of propagation, even waves of low length have a very high frequency in the range of hundreds of kHz, or more. This is much higher than a typical vibration transducer's range, especially when taking into consideration the influence of the mounting method on the frequency characteristic.

There are other classic noninvasive methods of diagnosis based on methods such as: magnetic, eddy current or powder methods. These methods are used only in cases of a lack of structural continuity i.e. for transverse and edge cracks. There are also ultrasound methods [3].

The diagnosis is largely based on vibroacoustic measurements. In the case of rotary machines, much information is given by observation of angular speed harmonics. Detecting gearbox faults, unbalance, misalignment of shafts etc. is based on spectrum FFT and order analysis. In the case of bearings, the amplitudes of the main harmonics rise at a very late stage of the fault, so to detect the onset of damage a crest factor or envelope demodulation is used. Those methods allow detection of low energy components in the vibration signal that are emitted during the early stages of demolition and are mostly not visible in normal spectral analysis or especially in the total vibration value. A very similar situation is found in the case of endurance testing performed on fatigue stands.

This paper concerns early crack detection based on vibration measurements using piezoelectric transducers. This is typically practical research. Testing was performed on real objects – rear suspension beams during a fatigue test.

1. TESTING METHOD

The aim of this research was selection of a method which would permit detection of a crack at early stages during the fatigue test. It was assumed that the measurements would be performed by piezoelectric accelerometers (with a widened frequency range) mounted to the test beam. The advantage of this kind of measurement is easy mounting, because contact transducers of that type may be mounted by wax, glue or magnets (drilling holes for studs is precluded because of material interference). Another advantage of using accelerometers is the fact that acceleration, with the increase of the frequency, rises in direct proportion to the velocity and in proportion to the square of displacement. Thus, accelerometers are very good for measuring high frequency vibrations.

The ENDEVCO transducers used have a frequency range of 5 Hz – 15 kHz which means that the sensitivity in this range varies by not more than ±1 dB. Above 15 kHz, the sensitivity rises, achieving a maximum value at the natural frequency of the seismic mass (the resonance frequency of the transducer). In this research the frequency range 5 Hz – 40 kHz was assumed (sampling at 102.4 kHz). The resonance frequency of the transducers used is approx. 50 kHz, so higher bands had been amplified because of measuring on a resonance slope.

For crack detection the absolute total value of vibration is not important; what is essential is the change of vibration, so the amplitude frequency's characteristic nonlinearity do not have high importance. (Amplification of high frequency vibrations is even advantageous.) The situation is different in the case of mounting errors (for example damping of glue at high frequency). That is why, before starting the test, it was assessed at what frequency range measurements with that kind of mounting are sure and first of all repeatable.

It was assumed that because the beam would be repeatedly bent by an actuator, any eventual crack would generate additional random type vibrations resulting from the rubbing of the crack edges, additionally amplified by the modal parameters of the object.

Because a vehicle suspension beam is a complex object, the cracks were not divided into longitudinal or transverse; instead the focus was d on detection.

The method used in this research was the observation of changes of the spectrum and time signal of vibration from two transducers mounted on the suspension arm and pipe near the probable location of the crack.

1.1 Statistical signal analysis – Time Domain

The main tool used during the test was time signal analysis. Time analysis is a basis of observation that can give parameters such as: maximum or peak values, rms and crest factor. The Root Mean Square (rms) is defined as:

$$RMS = \sqrt{\frac{1}{T}\int_0^T a^2(t)dt} \qquad (1)$$

where: T – oscillation period [s], a – vibration amplitude [m/s^2].

The Crest Factor is the peak to rms ratio [12]:

$$Crest\ Factor = \frac{Peak\ Value}{RMS\ Value} \qquad (2)$$

The Crest Factor describes the content of high amplitude impulses in the signal. High frequency impulses can be imperceptible in the rms value, so better results can be obtained by observation of the Crest Factor, which takes into account peaks in the signal.

Additionally, in diagnostics the application has kurtosis, which is the metric of flattening the distribution in comparison to a normal distribution. The kurtosis determines the concentration of results and can be used as main peak value estimator in the data analyzed [11]. It informs us how the results are concentrated near the mean value.

$$Kurtosis = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{X(i)-\mu}{\sigma}\right)^4 \qquad (3)$$

Where: N – quantity of samples, X(i) – value for i sample, μ - mean, σ – standard deviation.

2. THE OBJECT AND TEST STAND

The test beam was fixed on a stand that simulated the reaction forces during normal driving. The excitation force had a character of a sinus of stable amplitude and frequency. The location of the accelerometers is shown in fig. 1. The direction, fixing positions and area of expected cracks are presented in fig. 2.

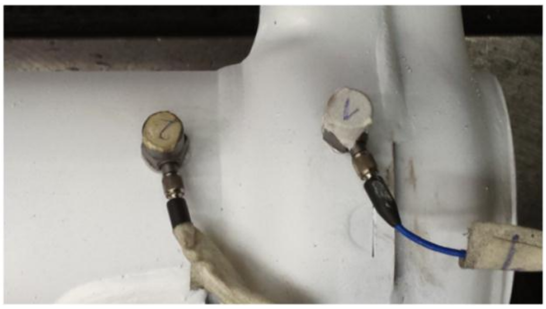

Fig. 1. Location of accelerometers on the beam

It was decided that the accelerometers should be as close to the assumed locations of cracks as possible, because the vibration emission was tested, not the modal parameters. In [9] the author lists two reasons why transducers should be at the nearest possible positions to the fault symptom (crack):

- characteristic damping of dissipated energy that rises with an increase of the frequency,
- modal parameters of the object.

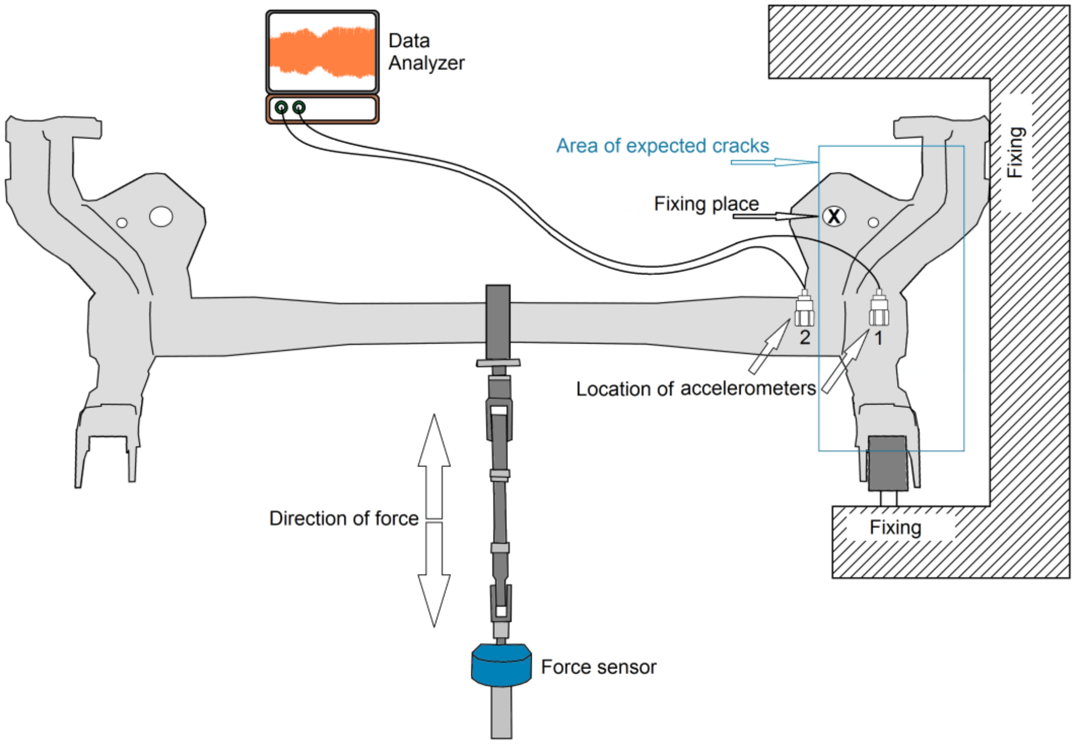

Fig. 2. Test stand scheme with expected location of cracks shown

3. TEST RESULTS

A fatigue test was performed on three beams and during this testing signals of vibration were recorded. The real location of the cracks is shown in fig. 3. On all beams cracks did not appear at the expected location: on the weld spot between accelerometers no 1 and 2.

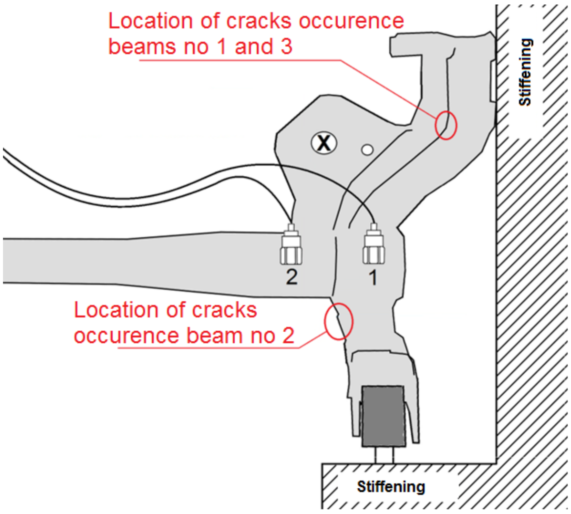

Fig. 3. Real location of cracks in the beams

The signal was recorded by vibration transducers for three beams. During the measurements, the FFT analysis was performed which is presented as 3d graphs in figs 4-6. For the first beam a vibration increase in the range of 12.5 – 13 kHz could be observed. For the second beam the FFT analysis showed an increase in a higher and wider frequency range. For the third beam there were some changes on the contour graph, but there was not an unequivocal vibration increase.

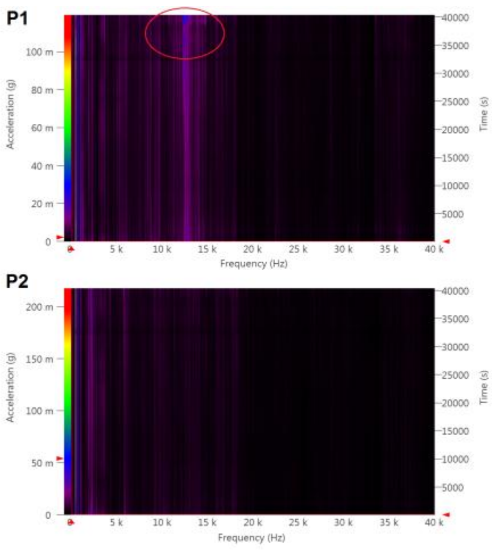

Fig. 4. FFT contour graphs in points 1 and 2 for beam no 1 with vibration increase shown

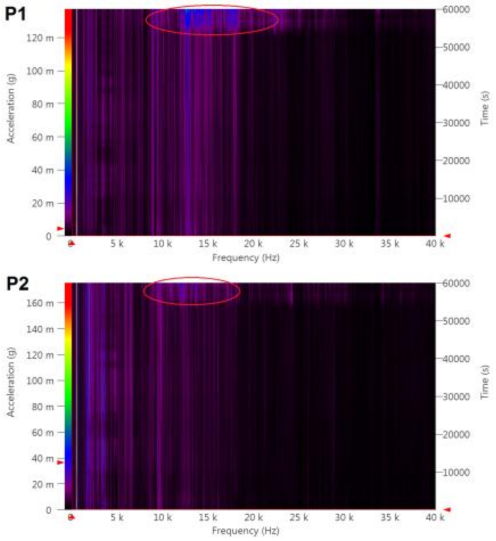

Fig. 5. FFT contour graphs in points 1 and 2 for beam no 2 with vibration increase shown

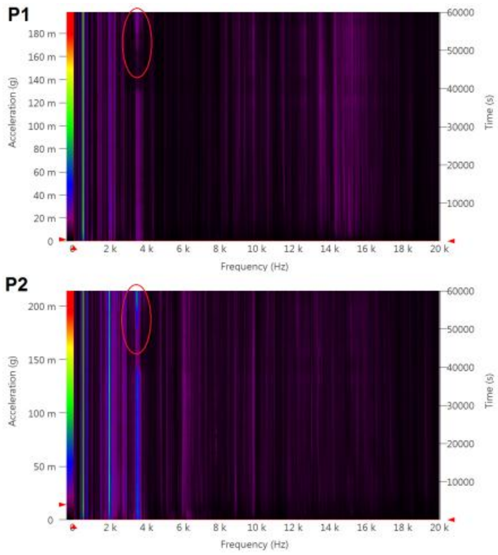

Fig. 6. FFT contour graphs in points 1 and 2 for beam no 3 with vibration change shown

3.1 Beam no 1

For the first tested beam the acceleration vs time graph up to 40 kHz is shown in fig. 7. There are four 30 s ranges shown, marked with numbers 1–4. The time of crack observation is also shown. There is a pronounced amplitude increase in the last phase of the test. The test was not recorded in its entirety, but the recording started at 190 000 cycles, which was right before the first crack was noticed (200 000 cycles). The peak that can be observed at approx. 1000s of the test might have been generated by this crack's appearance.

On the 30 s close-up of acceleration vs time graphs from the end of the test (fig. 8 C, D, G and H) it can be observed that there are low energy peaks that have some periodic connected to the frequency of the test. The range 3 differs from the range 4 that on the last sample the amplitude of peaks increased and additionally other kind of periodicity can be observed. For ranges 1 and 2 (fig. 8 A, B, E and F) the peaks are not present.

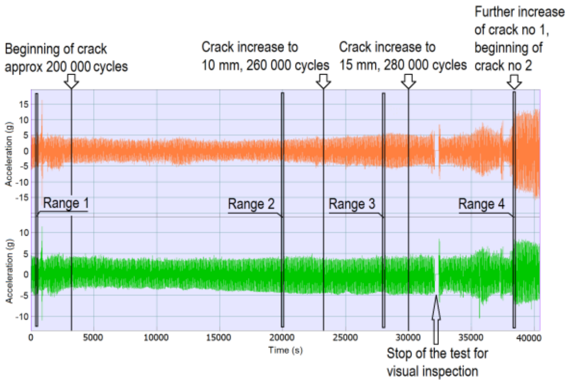

Fig. 7. Vibration time signal for beam no 1

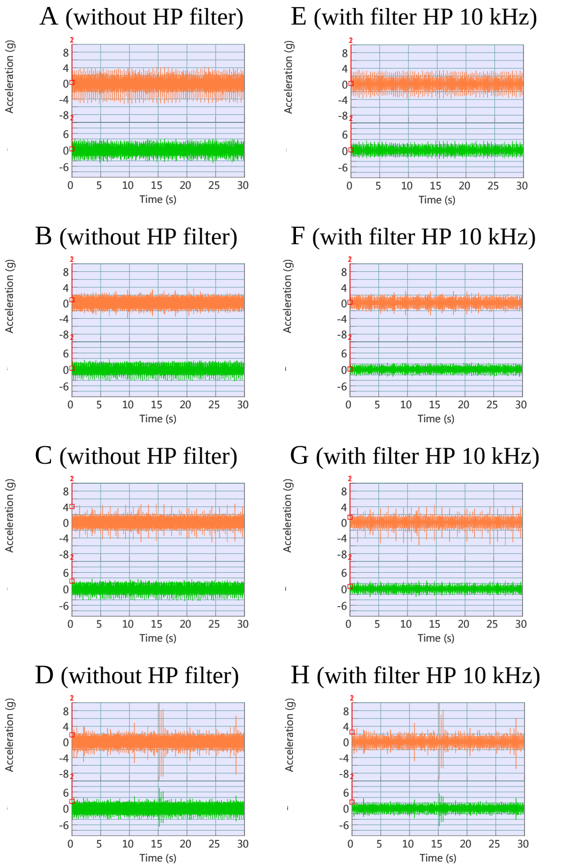

Fig. 8. The 30 s vibration samples of beam no 1

3.2 Beam no 2

For the second beam the whole test was recorded. At 170 000 cycles a crack was noticed. In the vibration acceleration vs. time plot (fig. 9) a high acceleration amplitude increase can be observed near the observation of crack. The amplitude later decreases.

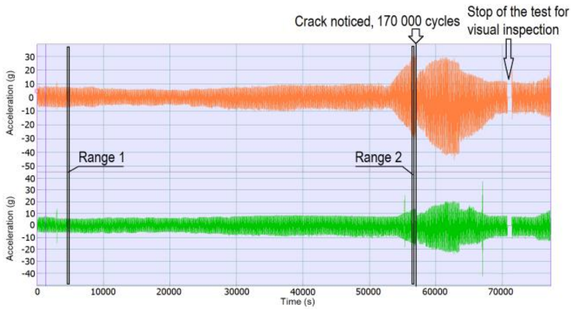

Fig. 9. Vibration time signal for the beam no 2

Because of the character of the whole test, the time analysis was performed for two ranges. The first range was at the beginning of the test, the second range was just before the detection of the crack. During the second range (fig. 10 B and D) high amplitude, low energy peaks can be seen. There was no periodicity that could be observed on beam no 1.

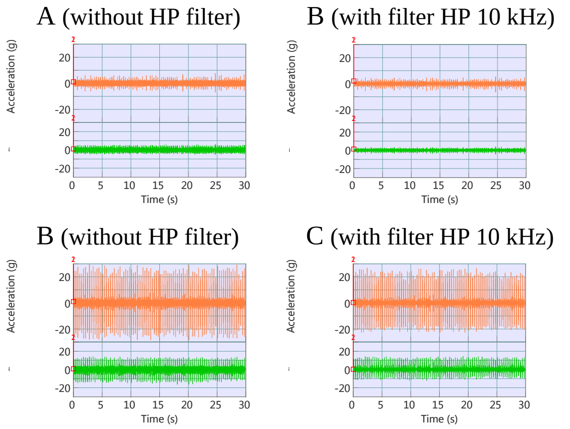

Fig. 10. The 30 s vibration samples of the beam no 2

3.3 Beam no 3

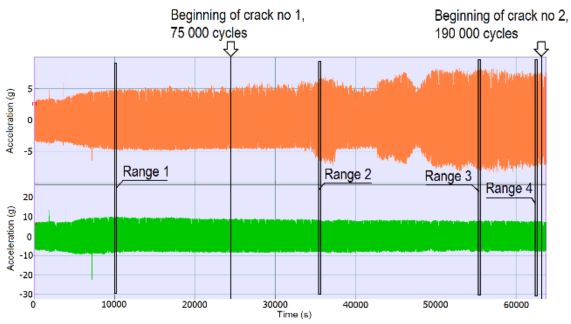

Fig. 11. Vibration time signal for beam no 3

Similarly to the two previous beams, the time analysis was performed with the use of the Time Domain analyzer for the ranges shown in fig. 11. The first sample (range 1) was taken from the stage when no crack was present (30 000 cycles - fig. 12 A and E). The next sample (range 2) was taken after detection of first crack (100 000 cycles). In that sample (fig 12 B, F) low energy peaks that were absent in the first sample can be observed (mainly in the signal from the accelerometer no 1). The next two samples (range 3 and 4) were taken at the end of the test (165 000 and over 190 000 cycles – fig. 12 C, D, G, H).

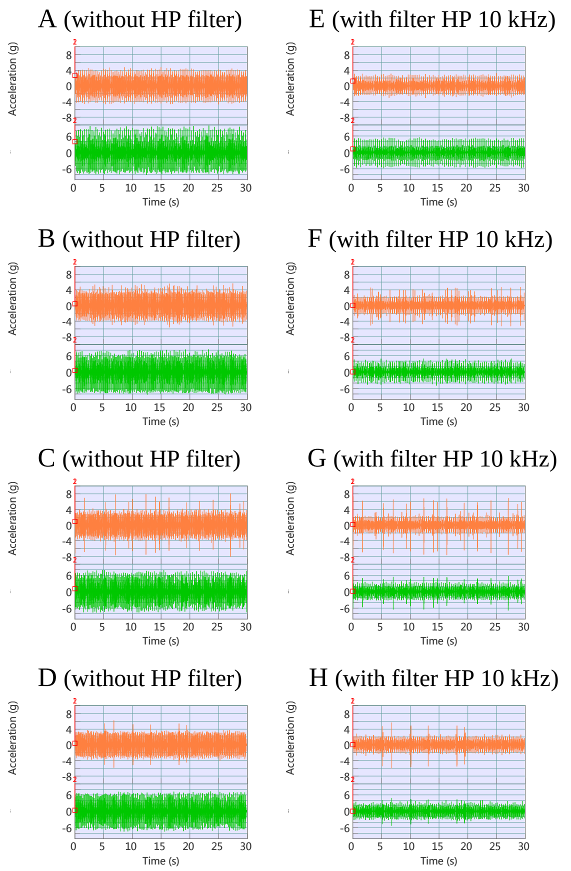

Fig. 12. The 30 s vibration samples of beam no 3

During range 3 a further increase of the amplitude of peaks can be observed. In range 4 the quantity of peaks and their amplitude decrease. In the case of this beam, the high influence of using an HP filter can be observed.

4. SUMMARY OF TIME DOMAIN ANALYSIS

For all time samples a statistical analysis was performed using Time Domain Analysis. Values of factors without using the HP filter are listed in tables 1 and 2 . Values with a 10 kHz HP filter applied are presented in tables 3 and 4.

In most cases, the signal from the transducer mounted on the suspension arm (accelerometer no 1) gave better results than the one mounted on the pipe (accelerometer no 2). The Crest Factor and Peak gave very good results. Only for the second beam, signal no 2 and without the HP filter were decreases in these values observed. This was caused because there was no peaks visible and the amplitude of vibration decreased. There might have been a problem with the mounting of the transducer that in this case could greatly limit the frequency range (down to below the range which is demanded to see the low energy peaks of a crack).

The HP filter greatly improved detection of cracks using the peak factor, which for beam no 3 gave a change of over 200 % (signal 1). For beam no 2 the HP filter decreased the Crest Factor because in this case the filter affected a change of the rms value. Without the HP filter the rms value of range 2 was 162% of the rms value for range 1. With the HP filter the rms value of range 2 was 325% of the rms value for range 1. This resulting in a reduction of the Crest Factor's effectiveness.

The RMS factor does not give good results, because this factor gives information about the energy of the signal - and peaks that are caused by a crack do not have much energy. Only for beam no 2 and with the HP filter was there a great rms increase. It was caused because in this case the quantity of peaks was much bigger, so it already had substantial energy.

For the kurtosis there was much dispersion. For the unfiltered signal and beam no 3 the increase was almost nil, but for beam no 2 it was over ten times. Using the HP filter that filtered the signal below 10 kHz much improved the results for this beam.

Table 1. Summary of statistic time domain results for beams – signal 1 without HP filter

Beams	Estimate	Transducer no 1				
		Range 1	Range 2	Range 3	Range 4	Increase
Beam no 1	RMS	0.29	0.32	0.33	0.41	143%
	Ktsis	6.49	11.32	16.01	67.59	1041%
	Pk	2.45	4.65	6.87	11.62	474%
	Pk-Pk	4.53	9.26	13.39	22.86	505%
	CrFact	8.57	14.72	20.64	28.42	332%
Beam no 2	RMS	0.42	0.68	-	-	162%
	Ktsis	9.21	54.69	-	-	594%
	Pk	5.21	18.10	-	-	348%
	Pk-Pk	9.88	35.30	-	-	357%
	CrFact	12.46	26.78	-	-	215%
Beam no 3	RMS	0.46	0.49	0.48	0.48	108%
	Ktsis	11.05	11.17	11.33	10.28	110%
	Pk	4.66	5.55	7.34	6.16	158%
	Pk-Pk	9.22	10.93	14.28	11.99	155%
	CrFact	10.17	11.26	15.19	12.90	149%

Table 2. Summary of statistic time domain results for beams – signal 2 without HP filter

Beams	Estimate	Transducer no 2				
		Range 1	Range 2	Range 3	Range 4	Increase
Beam no 1	RMS	0.51	0.41	0.41	0.42	123%
	Ktsis	3.99	6.64	7.98	13.07	328%
	Pk	3.27	4.51	5.38	6.84	209%
	Pk-Pk	6.45	7.86	9.96	12.05	187%
	CrFact	6.44	10.88	13.02	16.21	252%
Beam no 2	RMS	0.53	0.70	-	-	131%
	Ktsis	8.85	14.27	-	-	161%
	Pk	5.04	9.79	-	-	194%
	Pk-Pk	10.06	18.14	-	-	180%
	CrFact	9.48	14.09	-	-	149%
Beam no 3	RMS	0.66	0.70	0.63	0.67	111%
	Ktsis	19.26	18.34	16.60	16.26	118%
	Pk	9.19	8.10	7.42	7.34	125%
	Pk-Pk	16.92	16.01	14.73	14.55	116%
	CrFact	14.02	11.55	11.79	11.02	127%

Table 3. Summary of statistic time domain results for beams – signal 1 with HP filter

Beams	Estimate	Transducer no 1				
		Range 1	Range 2	Range 3	Range 4	Increase
Beam no 1	RMS	0.19	0.15	0.18	0.21	137%
	Ktsis	30.51	19.57	46.64	114.1	583%
	Pk	3.71	2.80	6.03	10.57	378%
	Pk-Pk	7.25	5.58	10.81	20.28	364%
	CrFact	19.20	18.33	32.90	50.46	275%
Beam no 2	RMS	0.23	0.75	-	-	325%
	Ktsis	42.26	127.0	-	-	301%
	Pk	5.81	27.38	-	-	471%
	Pk-Pk	10.77	51.46	-	-	478%
	CrFact	25.33	36.71	-	-	145%
Beam no 3	RMS	0.21	0.26	0.25	0.22	120%
	Ktsis	21.85	33.92	57.52	30.48	263%
	Pk	3.06	6.05	8.00	5.98	261%
	Pk-Pk	6.08	12.07	15.00	11.62	247%
	CrFact	14.27	23.55	32.07	27.11	225%

Table 4. Summary of statistic time domain results for beams – signal 2 with HP filter

Beams	Estimate	Transducer no 2				
		Range 1	Range 2	Range 3	Range 4	Increase
Beam no 1	RMS	0.18	0.15	0.16	0.19	122%
	Ktsis	23.63	22.27	23.71	36.42	164%
	Pk	3.41	2.71	3.08	6.81	251%
	Pk-Pk	6.19	5.35	6.01	13.09	245%
	CrFact	18.83	17.87	18.94	36.78	206%
Beam Beam no 2	RMS	0.20	0.53	-	-	263%
	Ktsis	26.30	50.87	-	-	193%
	Pk	4.46	14.29	-	-	320%
	Pk-Pk	8.53	26.60	-	-	312%
	CrFact	22.16	27.07	-	-	122%
Beam no 3	RMS	0.20	0.24	0.24	0.21	119%
	Ktsis	53.40	34.75	40.16	28.28	189%
	Pk	5.73	5.29	6.68	5.18	129%
	Pk-Pk	10.97	10.47	12.24	9.98	123%
	CrFact	28.44	22.12	28.36	24.73	129%

Table 5. Effectiveness of statistical parameters

Beams	Estimate	Signal 1 without filter	Signal 1 with filter HP 10 kHz	Signal 2 without filter	Signal 2 with filter HP 10 kHz
Beam no 1	RMS	143%	137%	123%	122%
	Ktsis	1041%	583%	328%	164%
	Pk	474%	378%	209%	251%
	Pk-Pk	505%	364%	187%	245%
	CrFact	332%	275%	252%	206%
Beam no 2	RMS	162%	325%	131%	263%
	Ktsis	594%	301%	161%	193%
	Pk	348%	471%	194%	320%
	Pk-Pk	357%	478%	180%	312%
	CrFact	215%	145%	149%	122%
Beam no 3	RMS	108%	120%	111%	119%
	Ktsis	110%	263%	118%	189%
	Pk	158%	261%	125%	129%
	Pk-Pk	155%	247%	116%	123%
	CrFact	149%	225%	127%	129%

5. CONCLUSION

This research has shown that measurement of the vibration in a wide frequency range with the use of simple time signal estimates can help with detecting cracks during fatigue testing of suspension elements such as car beams. The best results were acquired with the use of peak and kurtosis estimates with the application of a 10 kHz HP filter. In this case the change was always above 200 %.

The effectiveness of the Crest Factor method proved to be not as good as peak and kurtosis. Despite this fact, this method has great potential in testing when the forces are not stationary. This method has to be further tested with different settings to avoid problems that occurred for beam 2.

The FFT analysis showed some changes on graphs when cracks occurred but there must be more research done to ensure this type of cracks detection. The FFT 3d configuration needs more sophisticated analyzers than the time domain, which makes this method less attractive.

These results can be considered as an introduction to further research with many more beams tested. That would show the real effectiveness in the term of crack detection during this type of fatigue test.

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