AN EVALUATION OF TEMPERATURE INFLUENCE ON NATURAL FREQUENCY OF SELECTED FRICTIONAL ELEMENTS OF BRAKING SYSTEM

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Summary

In this study the temperature influence on the natural frequency of car brake drums is presented. Brake drums were tested with the determination of natural frequencies at chosen temperatures up to 500°C with modal analysis. The drums were excited by an impulse provided by a modal hammer, and then the sound response was measured with microphones. The test method, type of modal analysis used and the test stand are presented. Important theoretical issues for the article such as the natural frequency parameter and the transfer function description are adduced and then the practical application in a brake drums survey was visualized. Based on the measurements, the influence of temperature on the natural frequency of tested brake drums are presented. An acoustic response FRF plot was illustrated for one of the chosen drums. Two methods were used during the brake heating: a temperature increase method and a temperature decrease method. The results are shown in tables and plots with the influence shown on a percentage scale.

Keywords: modal analysis, brake drums, brake drum noise, brake drum natural frequency

1. Introduction

The comfort in production cars has emphatically increased in recent years. Travelling comfort is largely connected to a low level of noise. Today's cars generate much lower noise than ones produced in the previous century. The exterior noise level is regulated by law, but the interior noise level determines how many units of a given type of car will be sold.

To achieve contemporary sound quality inside the car, over many years producers have created and improved standards that applied more and more mechanisms and car

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elements, that without control, would probably influence it very badly . One of the elements that generates noise during operation is the frictional system of the braking system (pads – discs or linings – drums). Noise is generated by friction and random type drum excitation by the linings. The drum amplifies its natural frequencies. If the natural frequencies of the drum (or disc) are known, excessive noise generated by brakes can be easily predicted, because it is easier to select damping materials for known and stable frequencies.

During driving the brake drum changes its temperature, warming up rapidly in response to multiple braking events. Sometimes it can warm up to a temperature of several hundred degrees. In this study the influence of the temperature of the frictional system on brake drum's natural frequencies was investigated.

2. Test method

If a rigid body (such as a cube) is excited by an impulse (by a modal hammer, for example), its response spectrum is flat and does not have any modes in a wide frequency band. But if the object is more complex and less stiff, it has modes in the audible frequency range and when excited it generates sound dependent on the excitation force's characteristics and dynamic FRF (Frequency Response Function). This is due to the excitation of the modes that are in the structure and the rise of vibration, whose amplitude decreases logarithmically over time; the fading function depends on the damping of the material that the element is made of.

In further sections of this study the results of measurements designed to determine the influence of temperature on the natural frequencies of brake drums made of cast iron are presented. The drums were impulse excited by a modal hammer while the response was acoustically recorded by two ICP microphones. This eliminated the influence of transducer mass on the damping and the frequency of the modes.

The ambient noise level did not affect the result because the measurement was focused on the frequency of modes.

The drums were tested in the temperature range from ambient conditions to 500°C. The most important modes in the range up to 10kHz were chosen.

2.1 Transfer function FRF (Frequency Response Function)

Transfer function, in other words frequency response, is defined as a complex ratio of the output signal spectrum to the input signal spectrum as a function of the frequency [2], [3]:

$$H_{xy}(f) = \frac{F_y(f)}{F_x(f)}, \tag{1}$$

where $H_{xy}(f)$ is the transfer function from point x to point y.

$F_y(f)$ – Fourier spectrum on output of the signal measured in point y,
$F_x(f)$ – Fourier spectrum on input of the signal measured in point x.

During the test the output signal was the Fourier spectrum of the acoustic response, recorded by microphones, while the input signal was the force spectrum measured by the force sensor during the impact of the modal hammer.

2.2 Natural frequencies – methodology of determination

Each mode is characterized by three parameters: frequency, shape and damping. The frequency is estimated from the FRF characteristic directly after the measurement. The natural frequency is read as the maximum (peak) value of the FRF characteristic [1]:

$$|\alpha(\omega)_{max}| = \omega_r, \qquad (2)$$

For both values ω_a and ω_b localised on each side of the local maximum the amplitude is equal to half of the power, which equals: $\frac{\alpha_{max}}{\sqrt{2}}$. The damping ratio ξ may be calculated from the following formula [1]:

$$\xi = \frac{\omega_a + \omega_b}{2\omega_r}, \qquad (3)$$

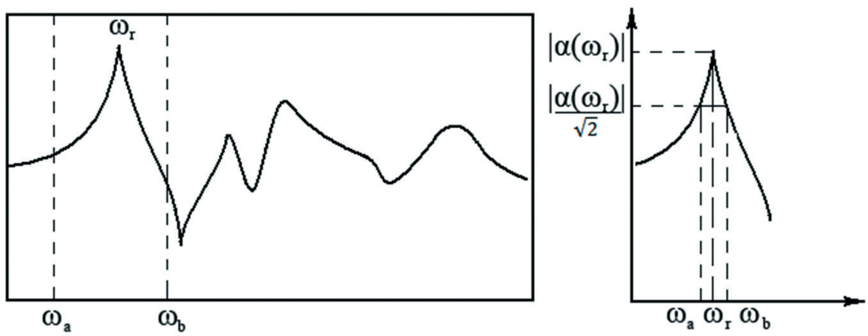

Fig. 1. The FRF characteristic with natural frequency shown [1]

The test body may have one or more natural frequencies. Those frequencies can be illustrated as following peak values ω_{rn} of the FRF characteristic.

This study is focused on the frequency value (in view of the test method, estimation of the damping was difficult and determination of the mode shape was even impossible). Microphones took the FRF characteristic directly, from which the following natural frequencies ω_{rn} were acquired.

The frequency is strongly connected to the mass and stiffness of the object. Given that the mass does not change with an increase in temperature, possible changes in stiffness or damping would impact on changes in the natural frequency.

2.3 Types of modal analysis

Modal analysis is divided into operational (OMA) and experimental (EMA). Experimental modal analysis is possible only when excitation force is known and measurable. In this case the method chosen does not really matter because of the focus on the frequency, but despite this fact, so the force transducer could easily be employed, the experimental analysis was carried out taking the excitation characteristic into account.

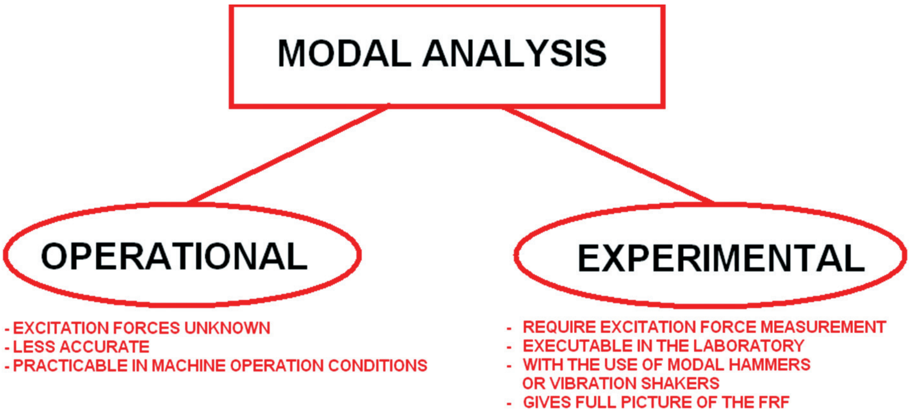

Fig. 2. Types of modal analysis

Modal analysis may be performed in different ways. The classical method of modal analysis is excitation of the object with a known (measured) force and acceleration response acquisition with the use of vibration transducers. Classic contact sensors (piezoelectric, piezoresistive etc.) can be replaced with non contact sensors (inductive, capacity, laser etc.) thereby eliminating the problem of the mass influence on the object. Unfortunately, the problem of sensor location still exists (it is possible that the sensor is positioned on the node, or on the arrow of the mode shape). Acoustic measurements eliminate that problem.

3. Test stand

Research designed to determine the influence of temperature on the natural frequencies of brake drums was performed. Acoustic measurements were performed because of the very high temperature. The next reason is that classic vibration transducers add new mass to the system, influencing the uncertainty of the measurement. The drum was suspended with steel rods to minimise the influence of the mounting on the sustain, and then put into an oven in which increasing temperatures were set. The test stand is shown in fig. 3 and the measurement scheme is shown in fig. 4.

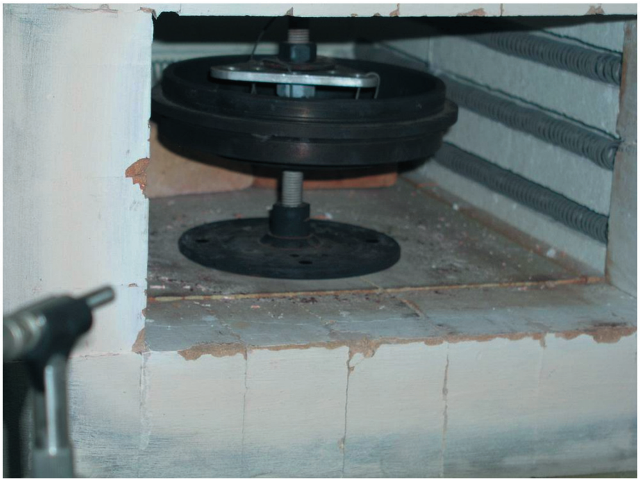

Fig. 3. Test stand for natural frequency determination of the brake drum – drum placed in the oven

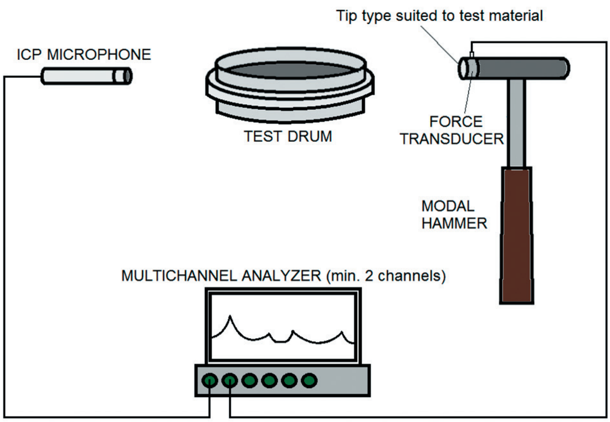

Fig. 4. Scheme of the test stand for natural frequency determination

4. Determination of natural frequency of drums by means of experimental modal analysis

The transfer function (FRF) was used to determine natural frequencies. The FRF was computed by the analyzer. To increase the signal to noise ratio the exp time window was applied, which is often used for impulse responses. The influence of the exp window was negligible because the damping ratio was not measured.

Because of the characteristics of the object and the modal hammer, it was focused on the frequency range up to 10 kHz, which was further limited to 9 kHz (during selection of modes). During the ambient condition measurement of the drum no 1 modes were selected and named 1 to 10 or 1 to 12 (according to the method).

In next steps the frequency shifting of each of mode was observed. During modal testing with the use of acoustic waves there is a risk of omission of mode because of for example microphone localization or nodes problems. In this case it was not important. Instead of focusing on is there all modes found in whole band analysed because this was not the test objective, it was focused on choosing modes that repeated in each temperature to be able to get characteristics in representative frequency band.

Determination of natural frequency was performed with two different methods. First method (hereafter referred to as temperature increasing method) was that the temperature in the oven increased from ambient to 500°C, with step of 50°C (from 100°C) and each time, after achieving the demand temperature and holding it for half an hour for stabilisation, the oven door was opened and the object was excited with a modal hammer.

The next method (hereafter referred to as 'temperature decreasing method') was the following: first the temperature in the oven was increased to 500 °C and after that time was allowed for the object to spontaneously cool down to the demand temperature. This method was helpful in terms of estimating the error of the chosen test method.

Because of the test conditions (research was not performed in an anechoic chamber, because hot objects taken from oven would cool down rapidly, which would have resulted in huge errors in estimating the temperature), the phase graph was not analysed because of high background noise, which might make the signal 'illegible' in that wide frequency band.

Measurements with the temperature increasing method were performed on two drums. Test results for different temperatures are shown in table 1. Frequency shifting in a percentage scale is shown in table 2. It can be clearly seen that for 500°C the average change is 5%.

On the frequency versus temperature plot (fig. 5) it can be seen that the frequency change is approximately linear relative to the temperature. It does not depend on the mode or on the frequency.

Table 1. Natural frequencies, drum no 1 – temperature increasing method

Temp. [°C]	Mode [Hz]									
	1	2	3	4	5	6	7	8	9	10
20	960.78	2514	3536	4370	4758	5238	6262	6480	7052	8720
61	952.54	2488	3502	4334	4718	5192	6207	6424	6976	8634
100	950.59	2478	3494	4326	4706	5182	6188	6408	6952	8606
150	944.52	2482	3484	4312	4688	5162	6164	6382	6924	8578
200	944.55	2466	3470	4300	4670	5146	6146	6340	6908	8568
250	944.56	2456	3460	4286	4656	5124	6126	6344	6878	8534

Table 1. Natural frequencies, drum no 1 – temperature increasing method, cont.

300	940.58	2450	3442	4268	4634	5102	6098	6292	6846	8498
350	932.51	2436	3420	4248	4606	5074	6068	6262	6810	8462
400	928.47	2422	3404	4224	4576	5040	6027	6230	6768	8420
450	924.45	2408	3384	4202	4550	5012	5990	6192	6728	8368
500	912.00	2390	3364	4170	4516	4974	5950	6150	6678	8344

Natural frequency change versus temperature in the percentage scale Δf

Temp. [°C]	Natural frequency change versus temperature in the percentage scale Δf									
20	0	0	0	0	0	0	0	0	0	0
61	0.86%	1.03%	0.96%	0.82%	0.84%	0.88%	0.88%	0.86%	1.08%	0.99%
100	1.06%	1.43%	1.19%	1.01%	1.09%	1.07%	1.18%	1.11%	1.42%	1.31%
150	1.69%	1.27%	1.47%	1.33%	1.47%	1.45%	1.56%	1.51%	1.73%	1.63%
200	1.69%	1.91%	1.87%	1.60%	1.85%	1.76%	1.85%	2.16%	2.04%	1.74%
250	1.69%	2.31%	2.15%	1.92%	2.14%	2.18%	2.17%	2.10%	2.47%	2.13%
300	2.10%	2.55%	2.66%	2.33%	2.61%	2.60%	2.62%	2.90%	2.92%	2.55%
350	2.94%	3.10%	3.28%	2.79%	3.19%	3.13%	3.10%	3.36%	3.43%	2.96%
400	3.36%	3.66%	3.73%	3.34%	3.83%	3.78%	3.75%	3.86%	4.03%	3.44%
450	3.78%	4.22%	4.30%	3.84%	4.37%	4.31%	4.34%	4.44%	4.59%	4.04%
500	5.08%	4.93%	4.86%	4.58%	5.09%	5.04%	4.98%	5.09%	5.30%	4.31%

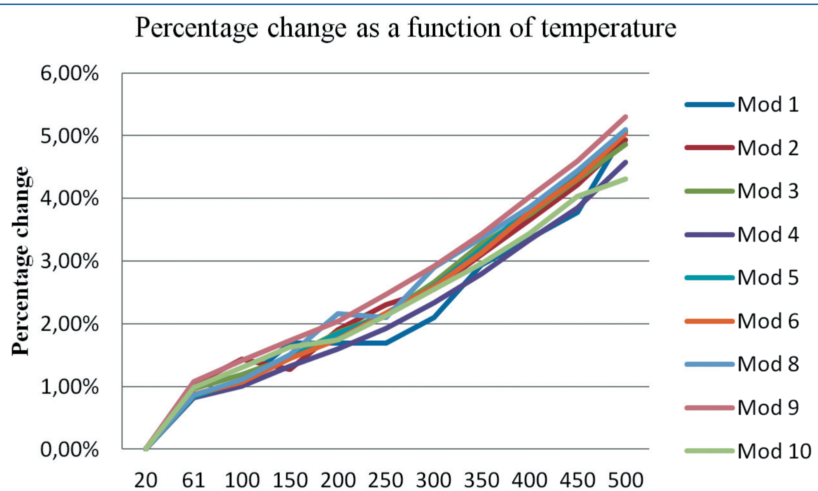

Fig. 5. Percentage change of natural frequencies of selected modes versus the temperature for the drum no 1 (temperature increasing method)

Drum no 2 was tested using the zoom function, focusing on the first mode. A sample FRF spectrum for ambient condition is shown in fig. 6

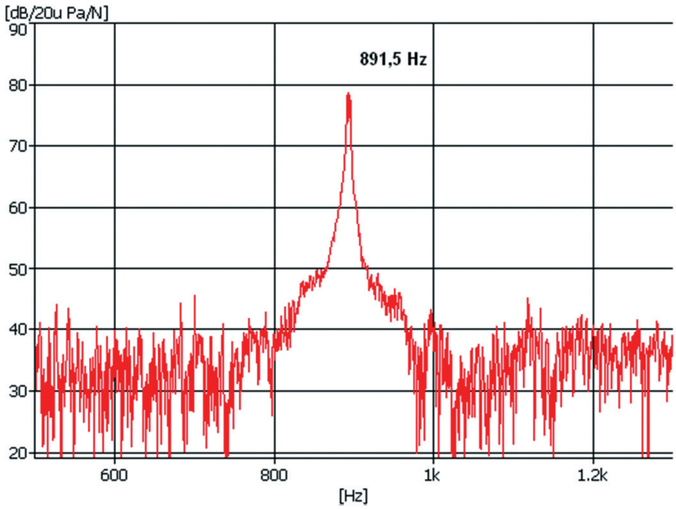

Fig. 6. Zoom – FRF characteristic (force spectrum – excitation, noise spectrum – response) of drum no 2, ambient condition (20°C).

In table 3 first mode frequencies for whole temperature range are shown. The results are similar to the results for the drum no 1. The percentage change versus temperature plot is shown in fig. 7.

Table 3. Frequencies of the first mode (zoom), the drum no 2, temperature increasing method

Temperature [°C]	f [Hz]	Δf
20	891.5	0
70	888.5	0.35%
90	886	0.63%
150	881.5	1.13%
200	877	1.64%
250	871.5	2.25%
300	865	2.98%
350	860.5	3.49%
400	859	3.66%
450	853	4.33%
500	850	4.67%

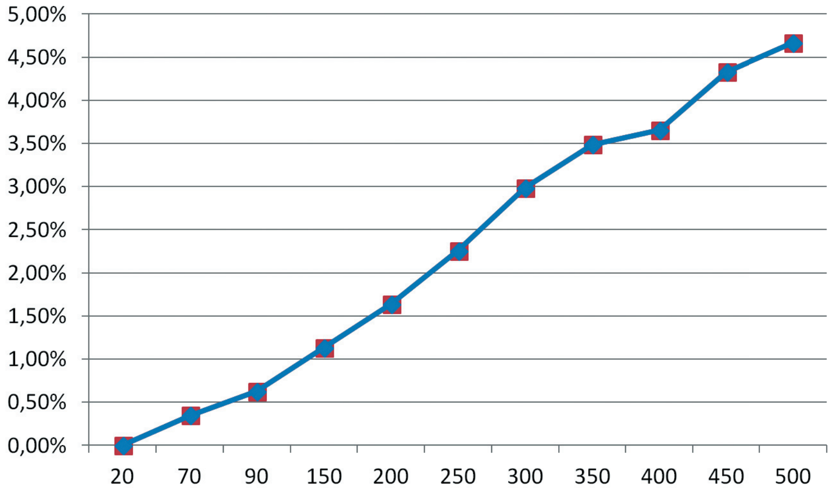

Fig. 7 Percentage change of natural frequencies of the first mode versus temperature for drum no 2 (temperature increasing method – zoom)

For drum no 1 an extra measurement with the temperature decreasing method was performed. The FRF spectrum for characteristic modes for two edge temperatures (20 and 500 °C), are shown in fig. 8 and 9.

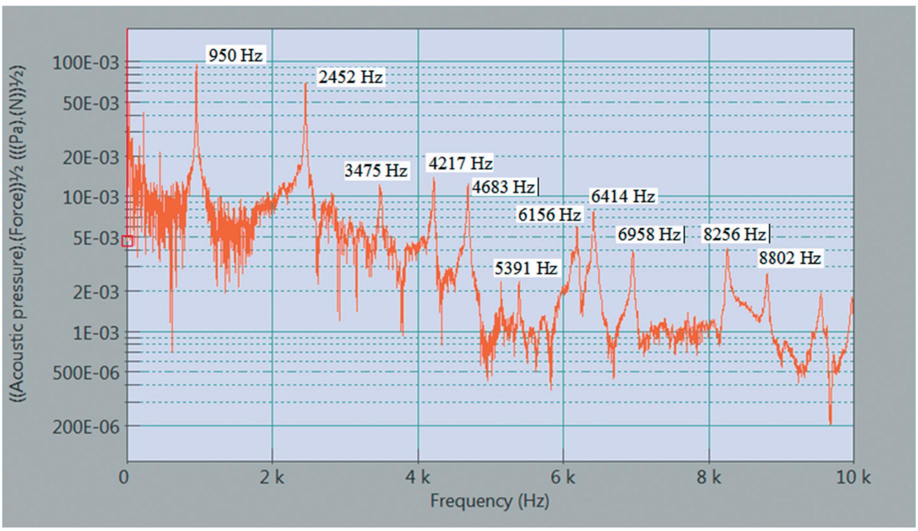

Fig. 8. The FRF characteristic (impact force spectrum – excitation, noise spectrum response) of drums in the ambient temperature (20°C) with modes chosen for further analysis marked

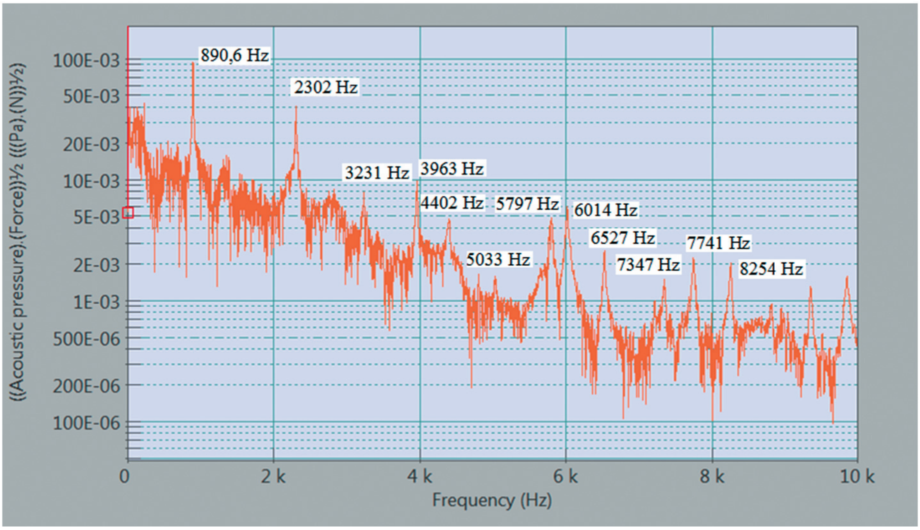

Fig. 9. The FRF characteristic (impact force spectrum – excitation, noise spectrum – response) of drums at a temperature of 500°C

The results for different temperatures are shown in table 4. Changes of frequency in a percentage scale are shown in the table 5. It can be observed that for 500 °C the average change is about 7%, which is 2% more than for the temperature decreasing method. frequency change of each mode plot is shown in figs 10 and 11. The increase is linear for whole range of temperatures and does not depend on the frequency of the mode.

Table 4. Natural frequencies, drum no 1 – temperature decreasing method

Temp. [°C]	Mod [Hz]											
	1	2	3	4	5	6	7	8	9	10	11	12
20	950	2452	3475	4217	4683	5391	6156	6414	6958	7820	8256	8802
117	939.06	2419	3441	4167	4622	5316	6081	6316	6863	7714	8142	8684
145	934.38	2413	3432	4155	4616	5301	6063	6298	6841	7700	8120	8655
192	929.69	2397	3414	4128	4584	5265	6022	6258	6800	7647	8069	8595
247	923.44	2383	3352	4102	4566	5234	5988	6227	6756	7608	8014	8547
291	918.75	2370	3361	4080	4534	5203	5961	6195	6720	7577	7973	8508
360	907.81	2342	3300	4033	4486	5133	5889	6118	6647	7480	7884	8405
406	903.13	2328	3273	4006	4450	5095	5845	6081	6609	7417	7836	8359
459	895.13	2309	3266	3980	4413	5052	5814	6041	6553	7380	7781	8275
500	890.6	2302	3231	3963	4402	5033	5797	6014	6527	7347	7741	8254

Table 5. Frequency change, drum no 1 – temperature decreasing method

Temp. [°C]	Natural frequency change versus temperature in the percentage scale Δf											
20	0	0	0	0	0	0	0	0	0	0	0	0
117	1.15%	1.35%	0.98%	1.19%	1.30%	1.39%	1.22%	1.53%	1.37%	1.36%	1.38%	1.34%
145	1.66%	1.61%	1.24%	1.49%	1.45%	1.69%	1.53%	1.84%	1.70%	1.56%	1.67%	1.69%
192	2.17%	2.28%	1.78%	2.14%	2.14%	2.38%	2.21%	2.48%	2.31%	2.25%	2.30%	2.39%
247	2.86%	2.88%	3.60%	2.79%	2.55%	2.98%	2.79%	2.99%	2.97%	2.77%	3.00%	2.97%
291	3.38%	3.44%	3.40%	3.34%	3.26%	3.59%	3.26%	3.52%	3.52%	3.19%	3.53%	3.44%
360	4.59%	4.64%	5.21%	4.51%	4.34%	4.96%	4.48%	4.78%	4.63%	4.49%	4.67%	4.67%
406	5.16%	5.29%	6.12%	5.23%	5.19%	5.77%	5.28%	5.44%	5.25%	5.39%	5.33%	5.27%
459	6.08%	6.14%	6.39%	5.92%	6.07%	6.65%	5.85%	6.13%	6.13%	5.93%	6.06%	6.30%
500	6.64%	6.50%	7.47%	6.38%	6.37%	7.09%	6.17%	6.62%	6.58%	6.41%	6.62%	6.62%

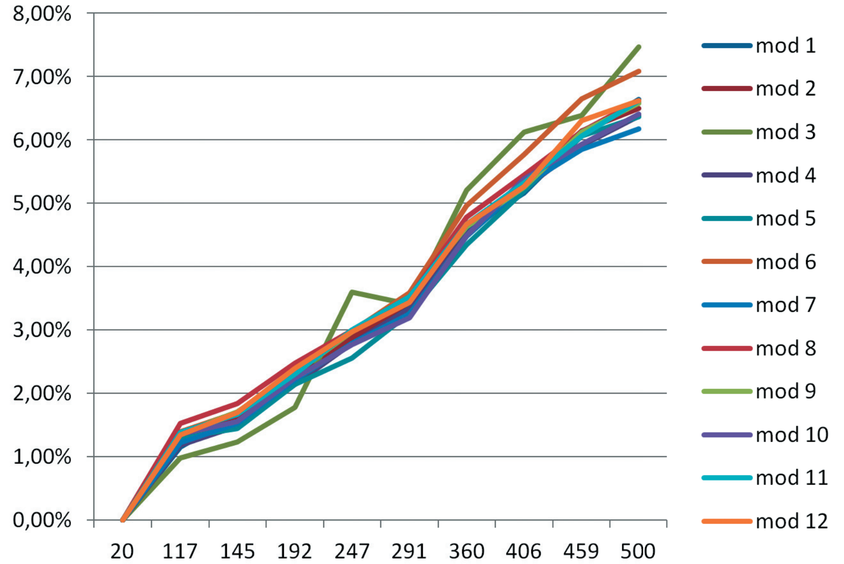

Fig. 10. Percentage change of the natural frequency of the chosen modes as a function of temperature for drum no 1 (temperature decreasing method)

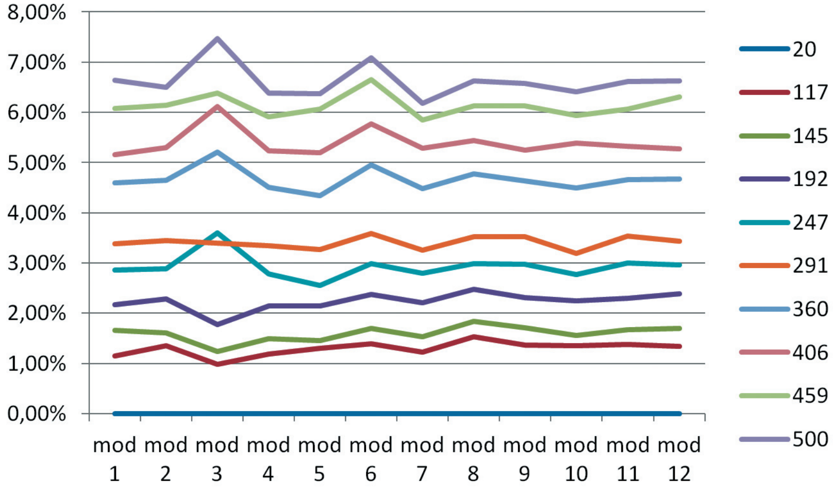

Fig. 11. Percentage change of natural frequency in the function of mode for the drum no 1 (temperature decreasing method)

5. Summary

The results for measurements with both temperature increasing method and temperature decreasing method confirmed the effect of temperature on natural frequencies. In the tested ranges (of temperature and frequency) the effect was linear and did not depend on the frequency. At a temperatures of 500 °C the frequency change measured with the increasing temperature method was about 5 % (both for drums no 1 and 2) and for the temperature decreasing method (drum no 1) was even 7 %. This means that for cast iron, which the brake drums are made of, heating it to a temperature of 500 °C decreases its natural frequencies by several percent. It is not much, but will significantly affect the audible noise characteristics.

A change of a few percent in the natural frequency compared to the temperature increase which is reachable during normal car operation increases the margin which designers should keep regarding tuning of the car's braking system. Otherwise, if the modal characteristic shifts in such a way that there will be coupling with other resonance that exists in the chassis during braking with warmed up brakes an annoying noise may result, which is impermissible in a new car.

It was found that the chosen method can influence the results in a fairly significant way. This is probably caused by the time duration of the warm up and stabilisation of the drums in the oven. Another disadvantageous fact was that measurements had to be performed with the oven doors opened. The above mentioned conditions had an influence on the results obtained.

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