ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2023
Issue 4/2023

87 – 92

10/4

10.24425/afe.2023.146682

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Forecasting the Natural Frequency of the Brake Disc casting

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Received 03.06.2023; accepted in revised form 08.09.2023; available online 22.12.2023

Abstract

The paper presents the results of calculations and measurements of the first natural frequency of castings of solid and ventilated brake discs made of gray cast iron of the EN-GJL-200 class. The tests were carried out for three types of chemical composition, taking into account the permissible minimum and maximum content of alloying elements. Numerical simulations of natural vibrations were carried out on the basis of our own production material databases. To determine the elastic properties of cast iron, the ultrasonic method with the measurement of the propagation velocity of longitudinal and transverse waves was used. Measurements were made directly on casts of raw discs of various thicknesses. The values of Young's modulus and Poisson's number calculated from ultrasonic measurements were used to define the stiffness matrix in the equilibrium equation, which is solved by the solver of the MSC Nastran program. A high compatibility between the results of numerical simulations and the results of experimental FRF frequency analysis was obtained. The differences between the calculated and actual values were at the level of several hertz, while the estimated average error of numerical simulations was 0.76%. It was also found out that cast iron melts for brake discs must be subject to strict control in terms of chemical composition. Slight deviations of the eutectic saturation coefficient from the optimal value cause a significant change in the first natural frequency of the brake discs, regardless of their geometry.

Keywords: Gray cast iron, Brake discs, Ultrasonic method, Elastic property, Natural vibrations

1. Introduction

Ensuring high quality brake discs and meeting the individual requirements of customers in the automotive industry forces foundries to conduct continuous research and development work aimed at improving individual stages of the production cycle. The cast brake disc, due to the safety and comfort of driving a car, undergoes a number of control tests, among which acoustic tests are of primary importance. Each disc, before it reaches the customer of the foundry, is subjected to a natural vibration test. Failure to meet the appropriate frequency range of natural vibration of the disk results in its rejection despite meeting all other acceptance criteria. The frequency range of natural vibrations and the geometry of newly implemented or modified brake discs are determined on the basis of numerical simulations of brake system vibrations. These simulations make it possible to optimize the vibroacoustic characteristics of the entire system and to determine the natural vibrations of its individual elements [1-4]. For years, the leading goal of acoustic experts has been to minimize vibration and noise during braking. The issue of generating the brake squeal is most often solved using the following methods: complex eigenvalue analysis or transient dynamic analysis [5-7].

In production conditions, obtaining the appropriate NVH frequency range (Noise, Vibration, Harshness) of the discs is related to carrying out a number of design and technological works at the foundry. NVH frequency forecasting procedures require the design of a pre-prototype of a raw brake disc cast, the development and manufacture of foundry equipment, the determination of the parameters and the course of melting of cast iron with the required chemical composition and operating properties, and then casting and machining of the discs. Subsequently, acoustic tests are carried out and the actual values of the eigenfrequencies of the cast pre-prototypes are determined. Most often, however, the results of these measurements are outside the frequency range set by the customer. In this case, a correction is made in the drawing of the disc, e.g.: other types of ribs are selected for ventilated discs, or the disc shape is slightly modified, and then the tooling for the production of this disc is modified and the validation process is carried out again until compliance is obtained with established NVH ranges. The above works significantly increase the production costs of brake discs and extend the implementation period.

The purpose of this study was to assess the reliability and accuracy of the results of predicting the natural frequency of solid and ventilated brake discs cast from EN-GJL-200 cast iron, whose chemical composition may be subject to slight changes in the production process. The paper assumes that from a technological point of view, the adequacy of the modal model of brake discs determines the method and accuracy of measuring the elastic properties of cast iron. The development and adaptation of our own production material database to the simulation program (Nastran Patran) will ensure more effective prediction of the natural frequency of brake discs without the need to make pre-prototype castings. In the case of metal alloys, elastic properties are determined using dynamic or static methods [8]. Dynamic methods dominate over static methods due to the possibility of performing tests on samples or finished products of quite any shape and size, ease of preparing samples for measurement and high accuracy of the obtained results. Taking into account the advantages and disadvantages of resonance and pulse techniques [9-11], as well as the possibility of linking the elastic properties of cast iron with the production process of brake discs, it was assumed that Young's modulus and Poisson's number tests would be carried out directly on castings using the ultrasound method and measurement of the propagation velocity of longitudinal and transverse waves.

2. Material and research methodology

The experimental part of the paper was carried out in one of the domestic cast iron foundries specializing in the production of solid and ventilated brake discs for passenger cars. The molds for disc castings were made using a specially designed model plate, which allows for imitating, in one technological operation, two solid discs and two ventilated discs with different wall thicknesses and nominal diameters. The dimensional range of the discs has been selected to cover the largest and smallest dimensions among the discs produced at the foundry. A 3D drawing of the concept of the casting method and the characteristic dimensions of the cast discs are shown in Figure 1 and Table 1.

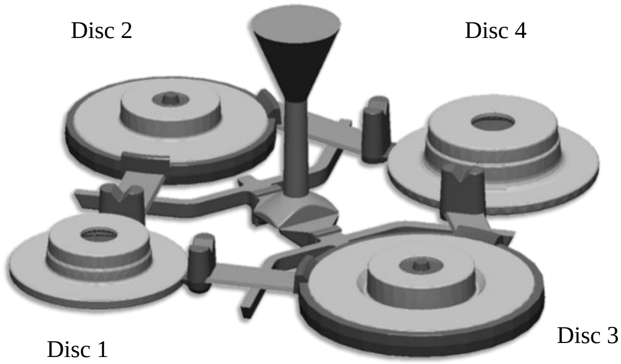

Fig. 1. 3D drawing of the brake disc casting concept

Table 1.
Characteristic dimensions of the tested brake discs

Disc code	Ventilation	Outer diameter [mm]	Inner diameter [mm]	Thickness [mm]	Weight [kg]
Disc 1	No	300	207	10	8.9
Disc 2	Yes	322	191	32	15.0
Disc 3	Yes	380	221	34	19.9
Disc 4	No	354	241	12	14.4

The material for the castings was gray cast iron modified with flake graphite with eutectic saturation coefficient S_C = 0.96-0.99 - EN-GJL-200 grade. The tests were carried out for cast iron with an optimal composition and for compositions with an acceptable maximum and minimum content of alloying elements, specified in the company standards and agreed with the contractors of the foundry. The chemical composition of cast iron is listed in Table 2.

Cast iron smelts were carried out in a medium-frequency induction crucible furnace with a capacity of 17 Mg, power of 8 MW and an inert lining. While pouring the molds, the cast iron was modified using the "liquid metal stream" method, which was carried out using an automatic dosing machine. For the modification, the Superseed modifier with a granulation of 0.2-0.7 mm was used, in the amount of 0.2% per portion of metal cast into the mold. Metallographic examinations were performed using a microscope with Olympus Stream Essentials software. The castings were subjected to microstructural analysis in accordance with the ISO 945 standard.

Table 2.
Chemical composition of cast iron for castings of brake discs (minimum - MIN, optimal - OPT and maximum - MAX content of elements)

Type of chemical composition	Chemical composition, wt.%										Eutectic saturation degree, S_C
	C	Si	Mn	P	S	Cu	Cr	Mo	Ni	Sn	
MIN	3.70	1.30	0.60	0.00	0.07	0.50	0.20	0.00	0.00	0.00	0.96
OPT	3.72	1.35	0.70	-	0.09	0.50	0.25	-	-	-	0.97
MAX	3.75	1.40	0.85	0.08	0.10	0.60	0.35	0.10	0.10	0.09	0.99

Ultrasonic tests were performed on the Olympus DL 38 Plus device using two broadband transducers VL - M110-RM and VT - V156-RM with a nominal frequency of 4 MHz. The first one was used to measure the velocity of the longitudinal wave and the second one to measure the velocity of the transverse wave. The applied broadband heads are characterized by a short pulse duration and enable the measurement of small thickness samples, eliminating the overlapping of successive pulses. The ultrasonic apparatus and heads met the PN-EN 12668-1 and PN-EN 12668-2 standards, respectively. Numerical simulations of natural brake disc vibrations were performed using the MSC Nastran software. Experimental measurements of frequency of natural vibrations (FRF analysis) were carried out in accordance with the EKB 2002 standard, using the Italsonic 2010 measuring station (Fig. 2). The casting was vibrated with a modal hammer of 0.1 kg and a head diameter of 15 mm. The emitted sound signal was recorded using a directional microphone with a frequency response of 100Hz - 10kHz

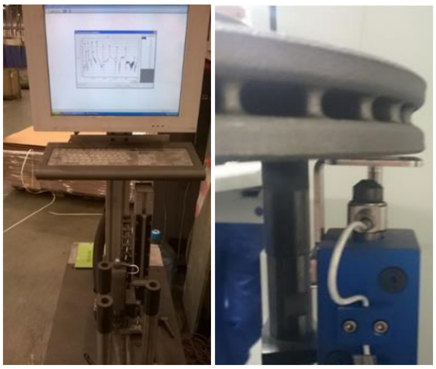

Fig. 2. Italsonic measuring station and hammer - microphone height position

3. Research results

3.1. Cast iron microstructure

A typical microstructure of the produced cast iron and the results of quantitative metallographic tests of the graphite precipitates and the metal matrix are shown in Fig. 3 and Table 3. It can be concluded that simple flake graphite occurs in cast iron, evenly distributed in the pearlitic matrix. The size of the graphite precipitates corresponds to size standards from number 3 to 5, and the largest share, over 90%, are graphite precipitates corresponding to the 4th and 5th standard of length (from 60 to 250 µm).

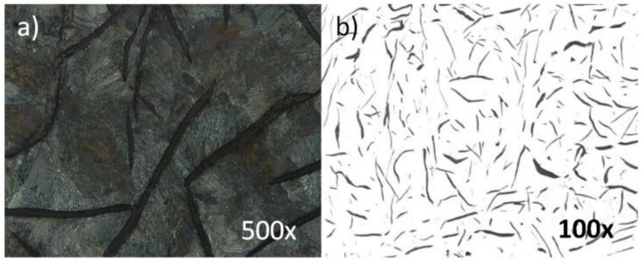

Fig. 3. Typical cast iron microstructure: a) sample pickled with 4% nital, b) sample without pickling

Table 3.
Results of quantitative metallographic tests of cast iron

Structural component feature	Disc code			
	Disc 1	Disc 2	Disc 3	Disc 4
GRAPHITE, %				
Graphite length				
5, %	63.87	72.56	66.05	73.45
4, %	18.73	24.23	24.94	22.86
3, %	4.16	3.21	9.01	3.69
Shape	I	I	I	I
Graphite distribution				
A, %	75	74	78	75
B, %	3	2	3	3
D-E, %	22	24	19	22
METAL MATRIX				
Perlite, %	94	94	95	94
Ferrite, %	5	5	4	5
Cementite, %	<1	<1	<1	<1

The amount of perlite in cast iron, using the designation according to the PN-75/H 04661 standard, corresponds to the P96 class. The structural parameters of the produced cast iron comply with the requirements of the brake disc contractors, as well as with the criteria presented in the Technical Conditions WT/054/PIMOT/93 [12].

3.2. Ultrasonic testing

Measurements of the velocity of propagation of longitudinal and transverse ultrasonic waves as well as the calculated values of Young's modulus (E) and Poisson's number (υ) of cast iron are summarized in Table 4. The presented ultrasonic wave velocities are average values determined based on three measurements for each brake disc. The elastic properties of cast iron were determined using the relationship [13]:

$$v = \frac{1-2\,(C_L/C_T)^2}{2-2(C_L/C_T)^2} \tag{1}$$

$$E = \frac{\rho C_L{}^2(1+v)(1-2v)}{(1-v)} \tag{2}$$

where: C_L – longitudinal wave velocity, C_T – transverse wave velocity, υ – Poisson's number, ρ - average density of cast iron - 7.149 g/cm^3, determined by hydrostatic weighing according to standard BN-75/4051-10.

Based on the obtained results, it can be concluded that for the tested chemical compositions of cast iron, the average value of Young's modulus varies in the range of 117-121 GPa, and for the optimal composition it takes the value of 120 GPa. In addition, the value of the standard deviation (determined from all 36 measurements) is 3.26 GPa. The repeatability and slight dispersion of the calculated E values are a particular advantage of the ultrasonic method as a method for determining the elastic properties of cast iron. As indicated in the introduction, the adequacy of the modal model of the brake discs is directly dependent on the accuracy of the material constants adopted for the calculations. The relationship between its geometry and Young's modulus was not disclosed for any of the disks. This property is only a material feature and in cast iron it depends on the eutectic saturation coefficient, graphite morphology and the type of metal matrix [14]. The Poisson's number determined on the basis of relation (1) for the examined range of changes in the chemical composition of cast iron is practically the same and amounts to 0.26-0.27.

Table 4.
Measurement results of the transverse V_S and longitudinal V_L propagation velocities of ultrasonic waves and the calculated values of Young's modulus and Poisson's number

Type of chemical composition	Disc code	Average velocity of longitudinal wave C_L (m/s))	Average velocity of transverse wave C_T (m/s)	Average value of Young's modulus (GPa)	Average value of Young's modulus by the type of chemical composition (GPa)	Standard deviation σ(E)	Average value of Poisson's number by the type of chemical composition
OPT	Disc 1	4520	2550	118	**120**	**3.26**	**0.27**
	Disc 2	4610	2560	120			
	Disc 3	4590	2590	122			
	Disc 4	4490	2590	120			
MIN	Disc 1	4580	2600	122	**121**		**0.26**
	Disc 2	4680	2600	124			
	Disc 3	4560	2590	121			
	Disc 4	4500	2580	120			
MAX	Disc 1	4480	2530	116	**117**		**0.26**
	Disc 2	4490	2560	118			
	Disc 3	4490	2570	119			
	Disc 4	4510	2520	116			

3.3. Numerical modal analysis and the measurements of natural frequency of brake discs

Numerical simulations of natural vibrations of brake disc were performed using the MSC Nastran software. This software is currently most often used by car manufacturers and allows for a comprehensive analysis of physical phenomena occurring during braking. Nastran enables the design of new braking systems through interdisciplinary optimization, which includes analyses of strength, modal, harmonic, thermal and comprehensive motion simulation. As a result of complex calculations, it is possible to determine the dynamic characteristics of the tested system, trace its behavior in various operating conditions and determine the topology of the disc structure. This paper is limited to presenting the results of calculations of the first natural frequency, which is the criterion for the acceptance of brake discs by customers of the foundry. This frequency is used to simulate the behavior of the disc with the brake pad at the moment of braking, and in production conditions it is strictly controlled based on FRF frequency analysis.

Numerical modal analysis was performed for all brake discs, assuming appropriate values of Young's modulus, Poisson's number and density, which were determined during experimental tests. These quantities define the stiffness-mass matrix in the equilibrium equation (3) on which the Nastran program is based.

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \qquad (3)$$

where:
M – mass (inertia) matrix, **C** – damping matrix,
K – stiffness matrix, **f** – vector of external forces,
$\ddot{\mathbf{x}}$, $\dot{\mathbf{x}}$, $\mathbf{x}$ – vectors of displacements, their first and second derivatives with respect to time *t*.

A boundary condition was assumed for the calculations - *no contact*, which corresponds to the actual condition during the frequency measurement at the Italsonic station. Solid models of full and ventilated brake discs were developed in the CAD Nastran environment and discretized with a finite element grid with the number of elements of 300 000 – 400 000 depending on the type of disc.

The results of calculations of the first natural frequency of the brake discs for the tested types of chemical composition are presented in Figure 4. This figure also shows the results of experimental measurements made at the Italsonic station.

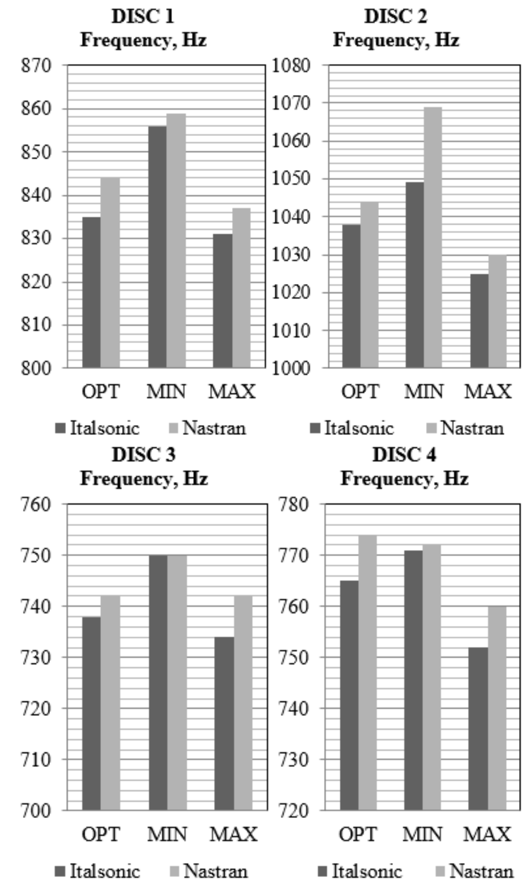

Fig. 4. Comparison of the results of calculations and measurements of the first natural frequency of the brake discs

On the basis of the obtained graphs (Fig. 4), one can observe the sensitivity of the first eigenfrequency (natural frequency) to small changes in the eutectic saturation coefficient S_C. Even a slight increase in the carbon (graphite) content in cast iron causes an increase in vibration damping and thus affects the natural frequency of natural vibrations. Regardless of the geometry, cast iron discs with a lower eutectic saturation coefficient (MIN composition) always have a higher natural frequency. Customers of the foundry very often impose limit frequency ranges at the level of changes of 3 - 5% in relation to the optimal value that was set by them in the order. It should be noted that all the results obtained as part of the research fall within the frequency range specified by customers. The results of numerical and experimental studies also indicate the lack of a clear relationship between the thickness, mass or diameter of the disc and the frequency of natural vibrations. All discs have their own individual natural frequency resulting from their shape. They evaluate solid discs (1 and 4) and ventilated discs (2 and 3) separately, however, a certain tendency of increasing the first natural frequency of castings with lower mass and smaller characteristic dimensions can be observed.

The comparative graphs presented in Fig. 4 also show a high compliance between the numerical simulation results and the experimental measurements of the first natural frequency of the brake discs. The differences between the calculated and actual values are usually at the level of a few hertz. A slightly larger deviation - 20 Hz was obtained only in one case, for the ventilated disc No. 2. A more detailed analysis of the adequacy of the modal model is presented in the next chapter.

3.4. Compliance assessment of numerical simulation results

In order to determine the consistency of the results in terms of the first natural frequency of the brake discs obtained from experimental tests and numerical modal analysis, the percentage error of the numerical simulation was calculated using the relationship:

$$\delta_S = \frac{(S-R)}{R} \cdot 100\% \qquad (4)$$

where: *S* – simulation result, *R* – actual result

The calculation results of the numerical simulation error are presented in Table 5
The obtained values of $\boldsymbol{\delta_S}$ indicate a high compliance between the acoustic measurements of the first natural frequency of the discs and the results of numerical simulations. The maximum error of numerical simulations does not exceed 2%, and its average value is 0.76%. It can also be concluded that the elastic properties of the cast iron determined by the ultrasonic method, on the basis of which the modal analyzes were carried out, are characterized by high accuracy and ensure the credibility of the results of numerical simulations.

Table 5.
Summary of the results of the first natural frequency of the brake discs and the percentage error of the numerical simulation

Type of chemical composition	Disc code	First natural frequency		Numerical simulation error
		Italsonic, Hz	Nastran, Hz	δ_S %
OPT	Disc 1	835	844	1.08
	Disc 2	1038	1044	0.58
	Disc 3	738	742	0.51
	Disc 4	765	774	1.18
MIN	Disc 1	856	859	0.35
	Disc 2	1049	1069	1.91
	Disc 3	750	750	0.00
	Disc 4	771	772	0.13
MAX	Disc 1	831	837	0.72
	Disc 2	1025	1030	0.49
	Disc 3	734	742	1.09
	Disc 4	752	760	1.06
Average error of numerical simulations				**0.76**

4. Summary

The conducted research showed that the use of the own production material database for numerical simulations of the natural frequency ensures high compliance of the calculation results with real measurements. The adequacy of the modal models expressed by the low error value of numerical simulations applies to both solid and ventilated brake discs. The use of the ultrasonic method with two measuring heads V_L and V_T, as well as the method of measurement (directly on castings of raw discs) allows for quick and precise determination of Young's modulus and Poisson's number of cast iron, as well as indirect control of the natural frequency of castings. The smelting of cast iron for brake discs must be strictly controlled in terms of chemical composition. Slight deviations of the eutectic saturation coefficient from the optimal value cause a significant change in the first natural frequency of the brake discs.

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