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EXPERIMENTAL INVESTIGATIONS OF NORMAL DEFORMATION CHARACTERISTICS OF FOUNDATION CHOCKS USED IN THE SEATING OF HEAVY MACHINES AND DEVICES Part I. THEORETICAL FUNDAMENTALS AND INVESTIGATIONS OF A STEEL CHOCK

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S u m m a r y

This paper presents a description and results of experimental studies of normal deformations occurring in foundation chocks made of steel and epoxy resin, used in the so-called rigid seatings (mountings) of heavy machines and devices on foundations. The studies carried out have shown that these kinds of seatings are not perfectly rigid. In both cases there are significant normal deformations which play an important role in the foundation bolted connections of machines and devices. These deformations should not be neglected in strength and dynamic analysis of these objects. Mechanisms and characteristics of the deformations occurring in the examined chocks made of steel and resin are different in terms of quality and quantity. These differences are important because they have a major impact on the technical and functional quality of the seating. The studies show that the foundation chocks cast of resin provide a better technical solution which ensures greater reliability and durability of the mounted objects. The entire elaboration consists of two parts, constituting separate publications. Part I describes first the technical and scientific aspects of the so-called rigid seatings (mountings) of machinery on foundations, and then the method and results of experimental studies carried out for a steel foundation chock, traditionally used for this purpose. Part II contains a description and results of similar studies carried out for a foundation chock cast of resin. Subsequently, a comparative analysis of the test results of two chocks was made and demonstrated why the foundation chocks cast of resin fulfill their tasks better than the traditionally used metal chocks.

Keywords: seating of machines, foundation chocks, deformations, experimental investigations,

Badania charakterystyk odkształceń podkładek fundamentowych stosowanych w posadawianiu ciężkich maszyn i urządzeń
Część I. Podstawy teoretyczne i badania podkładki stalowej

S t r e s z c z e n i e

W pracy przedstawiono założenia i analizy wyników doświadczalnych badań odkształceń normalnych podkładek fundamentowych, wykonanych ze stali oraz tworzywa epoksydowego, stosowanych w tzw. sztywnych posadowieniach ciężkich maszyn i urządzeń na fundamentach. Przeprowadzone badania w warunkach obciążeń dynamicznych wykazały, że występujące w tych posadowieniach połączenia maszyny z fundamentem nie są doskonale sztywne. W obu wypadkach występują znaczące

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odkształcania normalne, które odgrywają istotną rolę w fundamentowych złączach śrubowych maszyn i urządzeń. Występujące mechanizmy odkształcania oraz ich charakterystyka w badanych podkładkach ze stali oraz tworzywa różnią się pod względem jakościowym i ilościowym. Różnice te są istotne, ponieważ mają zasadniczy wpływ na techniczną i użytkową jakość posadowienia. Analiza wyników badań wskazuje, że podkładki fundamentowe odlewane z tworzywa stanowią lepsze rozwiązanie techniczne. Zapewniają większą niezawodność i trwałość posadowionym obiektom. W części I omówiono techniczne i naukowe aspekty dotyczące sztywnych posadowień maszyn na fundamentach, także metodę i wyniki doświadczalnych badań wykonanych dla stalowej podkładki fundamentowej, stosowanej tradycyjnie do tego celu. Część II zawiera opis i wyniki tych badań dla podkładki fundamentowej odlanej z tworzywa. Dokonano analizy porównawczej wyników badań obydwóch podkładek i wykazano, dlaczego podkładki fundamentowe odlewane z tworzywa lepiej spełniają swoje zadania od tradycyjnie stosowanych podkładek metalowych.

Słowa kluczowe: posadawianie maszyn, podkładki fundamentowe, tworzywo EPY, badania doświadczalne

1. Introduction

Proper operation, reliability and durability of heavy machines and technical devices, depend not only on their design and workmanship quality, but to a large degree also on the manner and quality of the performance of their mountings on the foundations. This applies in particular to machines and devices that generate large dynamic forces and vibrations, especially to piston machinery (big diesel engines, compressors, pumps etc.). Such objects are not mounted directly on the supporting surfaces of the foundations, but by using a number of chocks, which are located between the bearing surfaces of the machine base and foundation (Fig. 1). This results from the difficulty of proper fitting of the large bearing surfaces of the machine base to foundation, and very often also from the need of proper setting and adjusting the collaborating units, such as the engine with the gear box and the drive shaft of a ship or the drive motor with the crankshaft of a reciprocating compressor. Depending on the type of foundation chocks used, rigid or resilient seatings (machine connections with foundations) can be distinguished [1, 2].

This paper addresses only the issues concerning the seatings belonging to the group with rigid connections. It comprises a large class of different objects used in engineering practice. In conventional solutions for this type of seatings, the foundation chocks are made of metal (usually steel). Since such solutions have a large number of significant disadvantages (technical, economic and operational [3]), a new method of seating of machinery has been worked out, using foundation chocks cast of epoxy resins, specially developed for this purpose [4, 5].This method, primarily worked out to the needs of shipbuilding, has passed fully the practical examination under extremely difficult conditions occurring in the operation of maritime ships. It was found to be much more reliable in practice than the traditional method (with the steel chocks), and thus its widespread practical application in shipbuilding has already become a standard.

The new mounting technology of machines and devices using foundation chocks made of poured-in-place resin, because of many advantages, is now also used more frequently in seatings of a wide variety of land devices. In particular, it is very useful in the seatings of large reciprocating compressors, found in many industries including gas, oil and petrochemical production, transmission and storage. Large vibrations occurring in these devices and their effects are a substantial technical and economic problem. The problem turned out to be so sever and commonly widespread that the European Forum for Reciprocating Compressors (EFRC) has been founded in 1999. It associates research institutes, designers and manufacturers, installers and users of these devices from many different countries. In 2009 it published a study [6], which defines the tasks of the forum and gives general guidelines for the research and reduction of vibrations occurring in these devices.

Numerous studies have shown [4-14] that the weakest links in these devices are usually their traditionally made seatings and attachments to the foundation. Therefore, efforts have been made for some time now to improve the situation. Seatings are modernised by the application of state-of-the-art scientific findings. On the other hand, new materials, in particular the epoxy resins, specifically developed for this purpose are utilised.

The main goal of the research presented in this paper was to explain why the machinery seatings (mountings) with foundation chocks made of poured-in-place of polymer material are better technical solutions, with greater reliability and durability, than the traditional seatings with chocks made of steel.

2. Theoretical fundamentals

An important role in machinery seatings on foundations (Fig. 1a) is played by bolted joints. In the conventional classification [1], as well as in the current engineering practice [2], the discussed here foundation bolted joints, both with the traditional steel chocks (Fig. 1b) and modern chocks cast of resin (Fig. 1c), belong to the group of rigid structural connections (as opposed to the resilient connections with rubber chocks or special vibration isolators).

It is worth noting that the number of foundation chocks in the seatings of heavy machines and devices is usually much larger than three. It is often a dozen or even several dozen, such as in the main propulsion engine of a maritime ship (Fig. 1a). In such cases, the seatings form multiple statically indeterminate systems, which are very difficult to model and calculate, and also for practical realisation. This concerns in particular the exact fitting of the individual chocks. Even very small inaccuracies in their fittings can cause large unexpected assembly stresses and deformations in the whole mounted system. Shape errors, waviness and roughness of the contact surfaces can make a perfect fitting of metal chocks over their whole nominal contact surfaces practically impossible.

The true area of contact in such cases is only a very small part of their nominal contact area (Fig. 1b). This has very serious practical consequences. An exact fitting of the contact surfaces is possible and can be easily achieved in the case of the foundation chocks poured-in-place of resin (Fig. 1c).

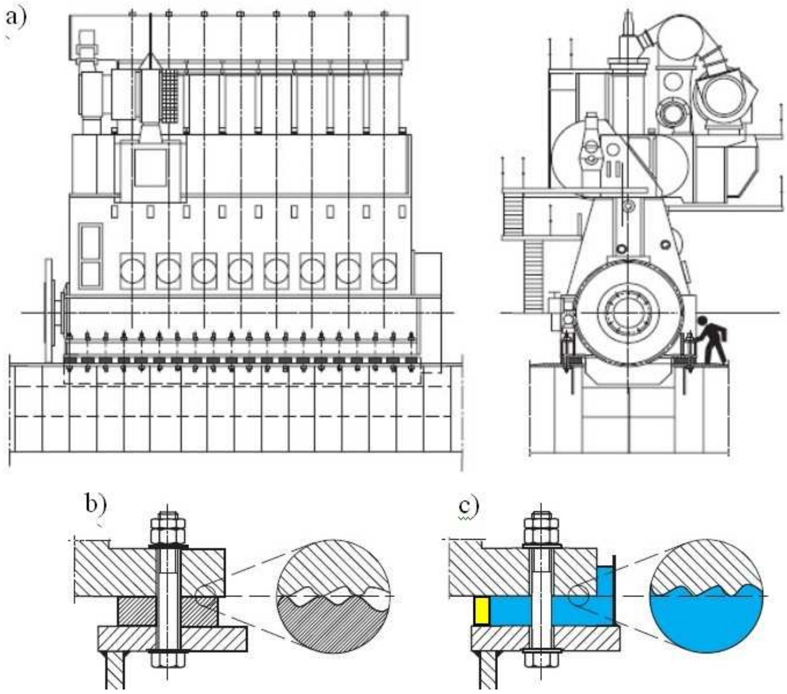

Fig. 1. A schematic of a marine engine seating (a) using chocks made of steel (b) and cast of resin (c)

The division of structural connections into two groups – rigid and resilient, adopted in theory and engineering practice, is purely contractual. In fact, there are no structural connections, and thus seatings, which are perfectly rigid. The classification of the foundation bolted joints considered here to the group of rigid connections, means practically that the deformations occurring in them can be omitted (as being small and insignificant). This is a major simplification of this problem, which hinders the proper understanding of physical phenomena occurring in the bolted joints and the role that they play in the mounted object.

In reality, complex deformation, vibration, friction and strength phenomena occur in such connections under operating conditions, which have a major impact, not only on the behaviour of bolted joints themselves, but often also on the vibrations, reliability and durability of the whole mechanical system in which they are located. Therefore, according to the recent studies [5, 9, 12, 14], machines and devices (with high dynamics), fixed to the foundations should be treated as integrated dynamic systems, consisting of three basic elements:

- the machine – treated as a vibration generator,
- the foundation (made of concrete or steel),
- the fastening system, which includes holding down bolts, metallic or resin chocks, sole plates embedded in the concrete, and steel structures (frames), if such are present between the machine and the foundation.

In such integrated dynamic systems the fastening system can not be considered as perfectly rigid. Many studies of other authors [5-12], as well as our own previous paper [14] show that fastening systems, in the traditional design (with steel chocks) are very often the weakest links of the entire complex mechanical systems, in which they are located. Good and very actual examples of such systems today are large reciprocating compressor units, working in the petrochemical industry, natural gas transmission compressor stations and other industries. Low quality and high unreliability of the fastening systems, made in the traditional manner during their installations, are currently the most common causes of excessive vibrations occurring during the operation of these devices. These vibrations lead ultimately to nut loosening, bolt cracking, breaking the interface contact surfaces, cracking and chipping the concrete foundations, cracking the machine bodies and oil leakages, fast wear of the machine parts, especially the crankshaft bearings and sometimes also cracking of the crankshafts [9]. The unreliability of the fastening system is the most common cause of various failures, unplanned downtimes, high repair costs and the resulting large production and economic losses. This poses substantial problems to the users of these devices.

Taking this into account the fastening systems of machines and devices that connect them with the foundations, can not be treated as perfect rigid connections. They must be seen and analyzed as certain complex mechanical systems consisting of several various interacting elements made of different materials. A reliable representative of such a system is a single bolted joint (Fig. 1b, c) which is fastening the machine bed to the foundation. An important role in this joint is played by a chock, which is an integral part of the joined elements. Together with the fastening bolt they form a complex structural node, with specific geometric, strength and dynamic characteristics, which depend on many different factors. Many studies have shown that in such complex structures, a significant impact on their behaviour under load, have not only the geometrical and material characteristics of their components, but also, to a large degree, the contact phenomena occurring in their contact interface. Very often, they have a major impact on the dynamics, reliability and durability, and this applies not only to the given structural node, but often also to the whole system.

Different physical phenomena present in these nodes are closely related to the deformations occurring in them, which arose in the process of assembly and are caused by the dynamic operational forces. Without an accurate knowledge of these deformations and the physical phenomena related to them one can not properly understand, formulate and solve problems, aimed at reducing the level of vibration and noise, and increasing the reliability and durability of machinery mounted on foundations. This applies not only to reciprocating compressors but also to a variety of other machines and technical devices. In particular, this knowledge is necessary to answer the basic question of why the use of resin foundation chocks in seatings of machinery is a better technical solution than the traditional solutions with steel chocks, although the strength of the resin is significantly less than that of steel.

3. Experimental procedure

Experimental studies were performed on a simplified axisymmetrical model of a foundation chock, under appropriate load conditions similar to those occurring in real foundation bolted joints of many machines and devices. In this kind of bolted joints, in close proximity to the bolts, there are locally axisymmetric stress states, which have a decisive impact on their deformation characteristics. This forms the basis for physical modeling and calculations as well as for the strength and vibration analysis of the bolted joints, generally accepted in the technical literature and standards.

The tested model of the foundation chock was made of ordinary steel St3 and had the shape of a ring with an outer diameter D_z = 80 mm internal diameter D_w = 30 mm and height H = 25 mm. The contact faces of the chock were turned. The surface roughness parameters amounted to: R_a = 4.67 – 6.04 μm, R_z = 23.28 – 33.22 μm.

Experimental studies were carried out on the servo hydraulic testing machine Instron Model 8501 Plus. A scheme of the test stand is shown in Fig. 2a, and the practical tests – in Fig. 2b.

The tested chock was placed between two flat end faces of steel discs, representing some segments of the foundation steel plate and the machine base. The faces of the steel discs, exerting pressure on the tested chock were machined (milled) and their roughness parameters amounted to: R_a = 13.50 – 14.53 μm, R_z = 50.20 – 59.59 μm. They correspond roughly to the surfaces of the metal foundations and the basis of the mounted devices.

The system, consisting of a steel chock and two steel discs acting on it, was subjected to compressive load (Fig. 2). In these tests special testing machine WaveMaker software (Instron) for dynamic tests was used. In dynamic tests all inputs and outputs are treated as functions of time. On the basis of this, special computer programs were developed, for several tests with different time courses and values of the loading force. Computer control of the individual tests provided them a high level of accuracy and repeatability of execution.

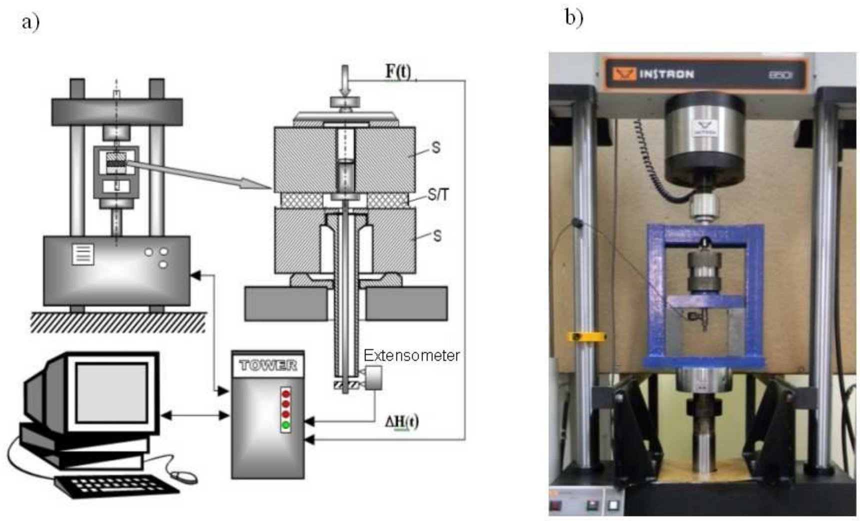

Fig. 2. A scheme of the test stand for investigations of the chock's deformations caused by the normal loads (a) and their tests on this test stand (b)

As a measure of the effective deformations ΔH for the tested chock the mutual approach of the steel discs faces, which were pressing against the given chock have been assumed. In this way, taken into account were not only the deformations of the material of the chock, with the height H, but also – what was very important in this case – the contact deformations occurring in two contact interfaces of the chock with the surfaces of the steel disks pressing against it. In real chocks these are surfaces of the foundation top plate (in this case made of steel) and the base plate of the mounted machine. In the adopted system efforts were made to ensure even distribution of surface pressure. An Instron extensometer was used for deformation measurements. The method of measurement is shown schematically in Fig. 2.

4. Tests and results

The research program included several tests with different time courses and values of compressive load presented below.

Test 1. First, compression tests were performed with a load varying linearly in time, according to an isosceles triangle gradually increasing in height. The runs and values of the load, established and executed on the test stand, and the deformations caused by them are shown graphically in Fig. 3. The rate of increasing and decreasing (rise and fall) of the force $F(t)$ varied while loading and unloading amounted to 10.8 kN/s. This resulted in rising and falling of the average compressive stresses in the chock at a rate of 2.5 MPa/s.

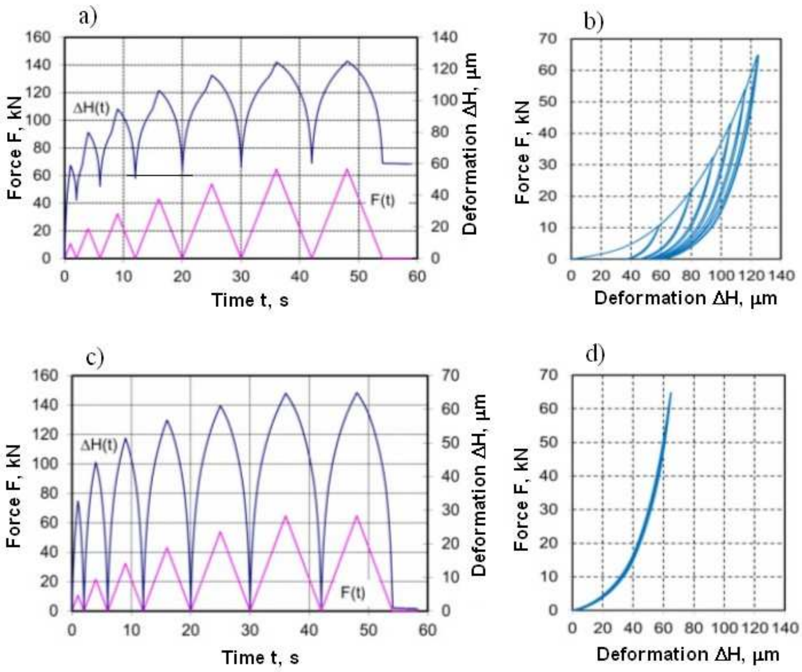

Fig. 3. Time runs of the given compressive loads $F(t)$ and the deformations $\Delta H(t)$ caused by them for the first (a, b) and third (c, d) loading cycles (having the same runs); (the maximum values of the surface pressures amounted sequentially to: σ_i = 2,5, 5,0, 7,5, 10,0, 12,5 and 15.0 MPa)

The studies have shown (Fig. 3), that linear runs of the load $F(t)$ cause significant nonlinear runs of the deformations $\Delta H(t)$. At repeated load cycles, (not greater than previous maximum values), deformations are in principle of an elastic nature. It is easily observable in Fig. 3c, d.

Significant permanent deformations occurring in the system under study at its first loading by a gradually increasing force can be explained by plastic deformations occurring on the asperity tops of the roughness of the interacting surfaces. Elastic deformations occurring in this kind of connections (belonging to the group of so-called rigid connections), clearly show that they are not perfectly rigid. These deformations have a significant impact on the installation and operating characteristics of the foundation bolted joints. They also determine the dynamic flexibility (stiffness) of the whole mechanical system in which they are present. They must be taken into account in modeling as well as in the static and dynamic analysis of the mounted objects. This applies, in particular, to the analysis of vibrations occurring in large reciprocating compressors, where the fastening systems are usually their weakest links and pose many problems to the users of these devices during operation [5 -14].

Figure 4 (curve 1) shows a stabilized deformation characteristic of the steel chock in the system under study. For comparison, this figure also shows the deformation characteristic (curve 2), determined from the simple Hooke's formula.

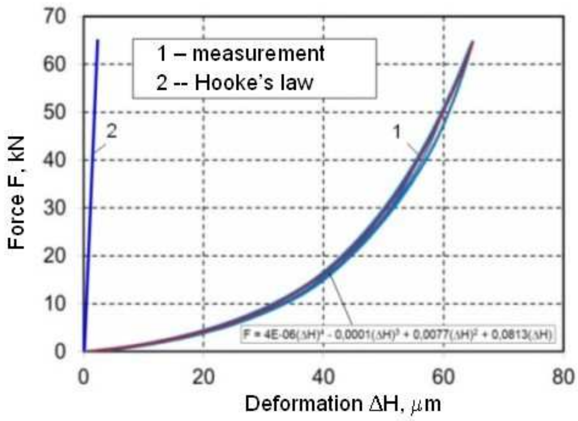

Fig. 4. The stabilized deformation characteristics of the tested steel chock in the system under study obtained experimentally (curve 1) and calculated according to Hooke's law for uniaxial compression (curve 2)

A comparison of these characteristics (Fig. 4) shows, that the linear characteristic determined from the Hooke's law, taking into account only the deformations of the material of the steel chock, demonstrates only a very small part of the total deformations of the chock in the system under study. The dominant role is played by the contact deformations occurring in the contact interfaces of the interacting components. They are purely elastic and have non-linear courses. They disappear almost immediately and completely after unloading of the system studied (Fig. 3c, d). This proves its stability. The elastic flexibility of the system is a variable quantity. It depends on the current load and decreases as it grows. A small hysteresis loop, shown in Fig. 4, is caused by deformation and friction phenomena occurring in a micro-scale in the contact of asperity peaks of the rough interacting surfaces.

Test 2. In this test, the system was loaded with a linear increasing force and gradually unloaded, wherein the unloading was only partial. The time runs of the given load $F(t)$ and deformations caused by it $\Delta H(t)$ are shown in Fig. 5a. Figure

5b shows the same measurement results in the co-ordinate system F - ΔH. They concern a stabilized system.

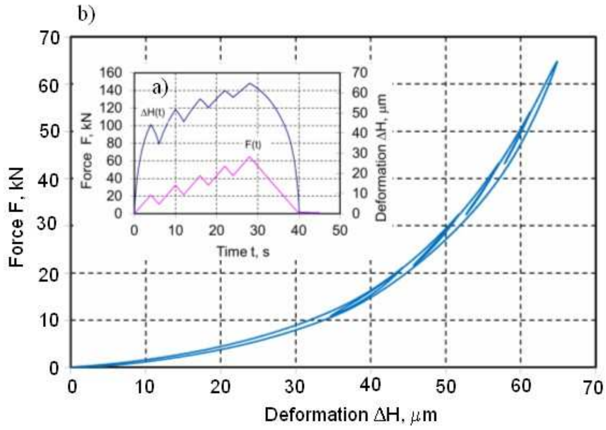

Fig. 5. Time runs of a linearly varying force $F(t)$ and the deformations $\Delta H(t)$ caused by it (a) and their mutual relationship in the co-ordinate system F - ΔH (b)

As the load increases, the deformation characteristic of the tested system grows in a continuous and smooth way (Fig. 5b), despite a partial unloading phase which occurs in the meantime. During the unloading and re-loading to the previous value, there is a clear deviation of the deformation from the main path of its growth. This results in the formation of some small hysteresis loops. They depend on the level (value) of the load followed by unloading. When re-loading, after the load has reached its previous maximum value, a further increase in deformations follows the curve that characterizes the deformations of the system when it is loaded by a force which is increasing in a continuous and uniform way. The curve of the total unloading of the system does not overlap with the curve of its loading. A hysteresis loop can easily be seen. The deformations of the system under study are non-linear-elastic. They disappear almost completely and immediately after its unloading (which can be clearly seen in Fig. 5a).

Tests 3 and 4. In the next two tests, the loads varied over time according to a sine function. Time courses of these loads and deformations caused by them are shown in Fig. 6a and 7a. Figures 6b and 7b show the results of the same experiments in the co-ordinate system F – ΔH. Figures 6a, b illustrate the influence of the amplitude of the variable exciting load (with a fixed mean value), and Figures 7a, b – the influence of the mean value of the variable exciting load (with a constant amplitude) on the deformations of the chock.

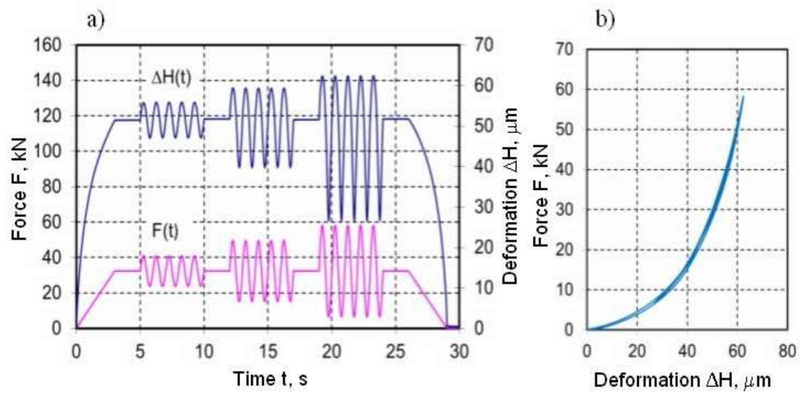

Fig. 6. Time runs of the sinusoidally varying force with a constant mean value (σ_m = 7.5 MPa) and three different amplitudes (σ_a = 2, 4, 6 MPa) and the deformations caused by it (a); in Fig. b) - results of the same measurements in the co-ordinate system $F - \Delta H$ (b)

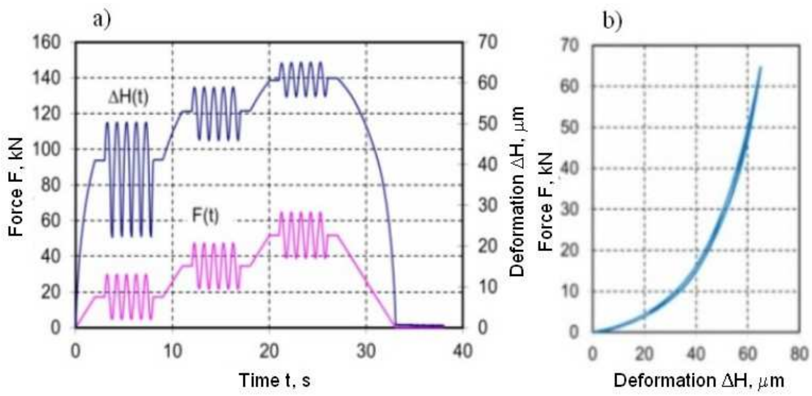

Fig. 7. Time runs of the sinusoidally varying force with a constant amplitude (σ_m = 3 MPa) and three different mean values (σ_a = 4, 8, 12 MPa) and the deformations caused by it (a); in Fig. b) results of the same measurements in the co-ordinate system $F - \Delta H$

Figures 6 and 7 reveal clearly the non-linear elastic features of the system under study occurring at dynamic loads. The responses of the system to harmonically varying excitation forces are deformations that have non-harmonic runs. The deflections are asymmetrical, which is clearly visible at higher excitation amplitudes (Fig. 6a) and at small mean values of the exciting force (Fig. 7a). The tested system is stable. Its flexibility depends on the current load and decreases as it grows.

Test 5. In this test, the effect of frequency of a sinusoidally varying excitation force on the deformations of the system is studied. Time runs of the exciting force and the results of this test are shown in Fig. 8.

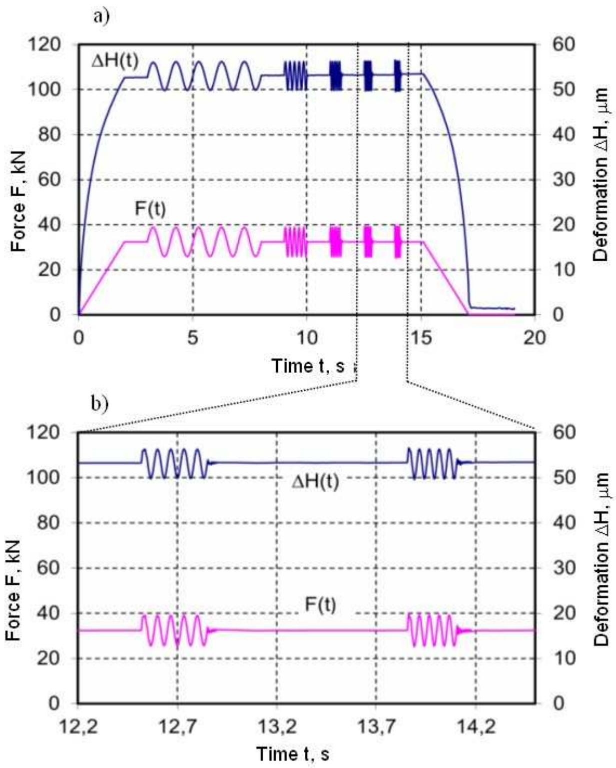

Fig. 8. Time characteristics of the given sinusoidal loads of different frequencies and the deformations caused by them in the system under study; Fig. b) is a part of Fig. a) in an enlarged time scale

These studies indicated that the scope of deformations for all selected excitation frequencies is practically identical, which means that the flexibility of this system does not depend on the frequencies of the excitations (over the range of their variation that was possible to achieve by using the Instron Model 8501 Plus).

5. Discussion and conclusions

The studies showed that in the foundation chock made of steel and subjected to compression between two flat steel surfaces, representing a steel foundation plate and a machine base, clear and well measurable normal deformations have occurred. These deformations, having during the first loading an elasto-plastic character, stabilize quickly, and can be well described by a non-linear elastic characteristic.

The total effective deformations of the chock are a result of linear elastic deformations of its material (subjected to compression), and the non-linear elastic contact deformations occurring in the contact interfaces of the chock and the steel elements pressing against it.

In the range of surface pressures (up to 15 MPa), essential for the foundation bolted joints of machines and devices, a dominant role is played by the contact deformations occurring in them. The material's deformations of the steel chock in this range are very small (with respect to the contact deformations). In many hitherto investigations, modeling and calculation methods of bolted joints, included also in the standard [15], taken into account are only the deformations occurring in the material of the connected elements, which are usually very small. Owing to this, bolted joints in the classical approach [1, 2] have been qualified to the group of rigid structural connections.

In real foundation bolted joints with metal chocks, a significant role is played by contact deformations. They have non-linear elastic characteristics, which determine substantially not only the behaviour of the fastening system, but to a large degree, also the whole mechanical system in which it is present. Therefore, a clear understanding and proper consideration of the deformations and the phenomena accompanying them can not be ignored when solving current problems, aimed at reducing the level of vibration and noise, and increasing the reliability and durability of machines and devices seated on foundations, both made of steel and concrete.

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