STUDIES OF FLEXIBILITY OF A STEEL ADJUSTABLE FOUNDATION CHOCK

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S u m m a r y

The paper presents a description and results of a flexibility study of a steel adjustable foundation chock (Vibracon® SM). Chocks of this type are used in so-called rigid seatings (mountings) on foundations of heavy machinery and equipment, which require precise alignment and adjustment. They are an alternative to conventional (ordinary) metal chocks or new generation chocks – which are ready-cast with specifically for this purpose developed polymer composites. Experimental studies were conducted in laboratory conditions on an original new chock. The characteristics of deformation for this chock were determined in conditions close to the operation conditions of such chocks. The results show that in the investigated system there are significant deformations of a non-linear-elastic character. They allow one to better understand and explain many complex phenomena occurring in real structural connections with such type of chocks. They also constitute an experimental basis for appropriate modeling and analysis of strength and vibrations occurring in such systems.

Keywords: foundation chocks, deformations, experimental studies

Analiza odkształcalności stalowej nastawnej podkładki fundamentowej

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

W pracy przedstawiono analizę wyników badań podatności na odkształcenia sprężyste stalowej nastawnej podkładki fundamentowej (Vibracon®SM). Podkładki stosowane są w posadowieniach, na fundamentach maszyn i urządzeń o dużej masie, wymagających dokładnego ustawienia i regulacji – osiowania. Stanowią alternatywę dla tradycyjnie stosowanych podkładek metalowych albo podkładek nowej generacji – wytwarzanych z kompozytów polimerowych. Badania doświadczalne prowadzono w warunkach laboratoryjnych z użyciem nowej podkładki. Wyznaczono charakterystyki odkształceń w warunkach zbliżonych do eksploatacji. Stwierdzono występowanie w badanym układzie dużego odkształcenia o charakterze nieliniowo-sprężystym. Przeprowadzona analiza wyników badań umożliwiła charakteryzację złożonych zjawisk występujących w rzeczywistych połączeniach konstrukcyjnych z użyciem tych podkładek. Stanowią również doświadczalną podstawę do procesu modelowania oraz analizy wytrzymałości i drgań, występujących w układach mechanicznych.

Słowa kluczowe: podkładki fundamentowe, odkształcenia, badania doświadczalne

1. Introduction

Machinery and equipment do not constitute a monolithic whole, but normally consist of a large number of parts and assemblies connected together in

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a permanent (bolted connections, forced-in joins) or kinetic way (guides, bearings). It is obvious that the static and dynamic behavior of the whole mechanical system of a machine, when it is in normal operation, depends on the behavior of the individual components and their connections.

Methods of calculation and rational shaping of individual components, because of strength and stiffness, have been well developed and used with success in design practice (e.g. FEM). However, the knowledge and methods of modeling and calculating structural connections, there are insufficient in relation to the current and rapidly growing needs in this area. The practice and numerous studies have shown that it is not components, but their connections that are often the weakest links in mechanical systems of many machines and much mechanical equipment. This applies not only to accurate manufacturing machines and robots, where connections and contact phenomena occurring in them have long been some of the main areas of research and practical activities aimed at increasing the quality of these devices [1-7], but also heavy machinery and equipment, such as large internal combustion engines, compressors, etc. Studies conducted in this area, previously on ship machinery and equipment [8], and lately on large reciprocating compressors [9] (operating in natural gas compressor stations and in the chemical industry) have shown, that the main reasons for the occurrence of large vibrations, fast wear of many parts (mainly crankshaft bearings), numerous failures and unplanned downtime, and many problems and costs associated with them, are the low quality and high unreliability of traditionally made seatings and methods of fixing these objects to foundations.

Large reciprocating compressors, like much other heavy machinery and equipment, are mounted and fastened to foundations in the so-called rigid manner. This way of perceiving and treating these connections is much simplified, which has its consequences in the modeling and analysis of the static and dynamic properties of whole systems. An important fact should be noted at this point, and namely that "rigid mounting" is a purely theoretical concept. In real foundation bolted connections, as well as in many other so-called rigid connections of structural components, there are complex phenomena of vibration, frictional and strength nature, which often have a significant influence on the dynamics, reliability and durability of the entire system. Articulated reciprocating compressors discussed here, which are a classical example of the occurrence of such situations, are not an isolated phenomenon.

In the traditional method of seating of large reciprocating compressors on foundations normally ordinary compensatory chocks made of steel have been used. Due to numerous disadvantages of this method today foundation chocks ready-cast of special plastics are used for this purpose. Significant benefits arising from this progress are presented in [8, 10]. An alternative to traditional (ordinary) steel chocks and modern - ready-cast chocks of plastic are the special adjustable steel chocks Vibraon® SM. Because these chocks were also used in

the installation of some modern compressors (Fig. 1b), and the company's catalogue [11] and other sources available on the Internet do not contain any information on their stiffness, it was decided to investigate this problem within the framework of the ongoing research project concerning the issues. A description and results of these investigations are presented in this paper.
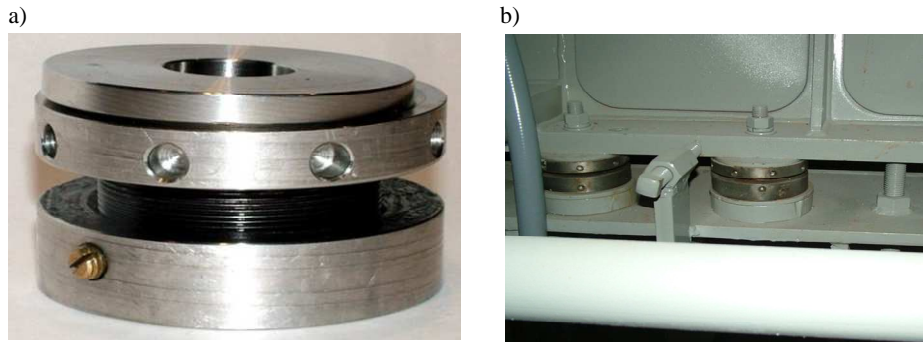
a)   b)

Fig. 1. A universal adjustable foundation chock Vibracon® SM: a) a general view, b) in the seating of a reciprocating compressor

2. Characteristic of the Vibracon® SM'' chocks

The object of the research presented in this work, is a universal adjustable steel chock Vibracon® SM'', shown in Fig. 1a. Chocks of this type, manufactured in various sizes, are used in seatings of heavy machinery and equipment on foundations and assembly (bolted connections) of large structural components requiring precise setting and adjustment. Despite what the name suggests, they are not in any way vibration isolation chocks, designed for elastic fastening of machines. They are intended for rigid fastening. Their universality means here that they can be used in seatings on the foundations and installation of all types of machines and technical equipment, instead of the traditional (ordinary) rigid steel chocks, which require laborious alignment during assembly, shims or modern chocks-cast from a specially designed plastic [8-10].

Their advantage is the ability and ease of height adjustment, and their spherical washer, provides good contact with the bearing surfaces of the foundation and base of the machine. This ensures an even distribution of pressure on the bearing surfaces of the chock, even when it comes into contact with surfaces which are not parallel. The nonparallelity between the bearing surfaces of the foundation and the basis of the machine can amount to up to 4°.

An important advantage of the Vibracon® SM chocks is also the fact that they can very quickly be applied in the work of an assembly, without the need for any kind of treatment (associated with matching) and the time needed to cure chocks cast of plastic. In addition, these chocks can be re-aligned and used repeatedly. A certain disadvantage of these chocks is, however, their relatively high price.

The possibility to adjust the height of the chock does not mean that it can be used for aligning the height of an assembled object. For this purpose special adjusting screws are used as shown in Fig. 1b.

Vibracon® SM adjustable chocks, as well as alternatively used ordinary steel chocks and ready-cast polymer plastic chocks, despite the fact that they are intended for so-called rigid fastening of machines and equipment, are not perfectly stiff. They have certain flexibility characteristics, which should be duly taken into account in accurate calculations of the foundation bolted joints and in modeling and dynamic analysis of the whole system, consisting of machinery, foundation and fastening system.

3. Experimental studies

The experimental studies of the Vibracon® SM chocks were conducted in the Material Strength Laboratory at the West Pomeranian University of Technology of Szczecin, on a servo-hydraulic testing machine, model 8501 Plus, manufactured by INSTRON, using special equipment and computer software. A professional computer program WAVEMAKER has been used, which is designed for dynamic tests. The difference between dynamic and static tests is that the input and output quantities are both treated as functions of time. The applied program ensured an exact implementation of any given cycles of loads and automatic recording of the measured deformations induced by these loads. A schematic diagram of the test system is shown in Fig. 2a, and the tests performed on the testing machine – in Fig. 2b.

The tests were conducted on a new Vibracon® SM 12 chock, with a nominal diameter $D = 60$ mm, hole diameter $d = 15$ mm and a nominal height of $H = 34$ mm. The usable height of the chock can be varied continuously between 30 to 38 mm. The maximum load for the chock is 48 kN. The tested chock was placed between two flat ends' faces of steel disks and axially compressed according to the strictly determined programs. The surfaces of steel disks, pushing down on the tested chock had been milled and their roughness parameter $R_a = 13.5 - 14.5$ μm. The disks represented in the tests the bearing surfaces of a steel foundation and mounted machine. The roughness parameters of the top and bottom surfaces of the tested chock were $R_a = 0.87 - 0.90$ μm and $R_a = 2.28 - 1.37$ μm, respectively. The tests were conducted for dry contacts.
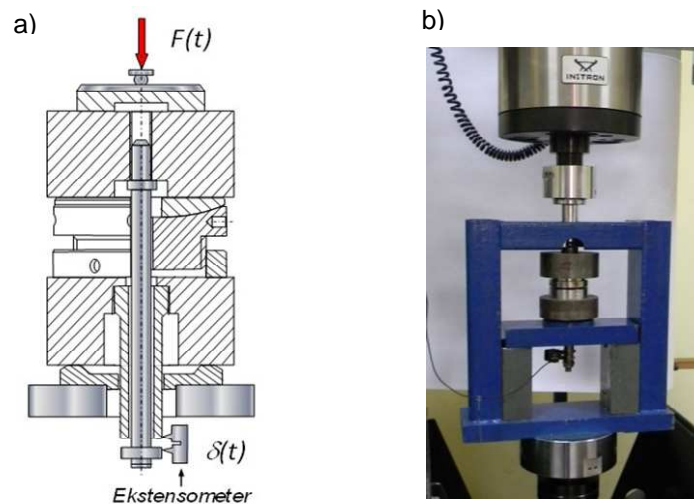
Fig. 2. The investigated system and the method of measuring
deformations (a) and the tests conducted on a testing machine (b)

The test system and the method of its loading have been chosen as to
provide axial symmetry and uniform distribution of pressure. This corresponds
well to the conditions of their use in practice (Fig. 1b). As a measure of the
normal deformation of the tested system we adopted the change of the mutual
distance between the pressing surfaces of the discs. Deformations were
measured in the axis of symmetry of the system, using the INSTRON
extensometer, as shown in Fig. 2a.

Experimental studies were carried out for several different loading
programs. First, it was carried out with loads increasing and decreasing in a
linear manner over time (with a constant speed $v = 10.7$ kN/s) and then with
sinusoidally changing loads. The given load runs and the deformation runs
caused by the load are presented in graphs, in the form obtained directly from
measurements, recorded and processed by the computer (without their
qualitative treatment).

Figure 3a shows the time runs of the given load cycle, $F(t)$, changing
linearly according to an isosceles triangle progressively increasing with height,
and the deformation runs $\delta(t)$ induced by these loads. Having recorded with
great accuracy the time runs of the force $F(t)$, as an input quantity, and the
deformation runs $\delta(t)$, as an output quantity, then they can be properly processed
and subjected to detailed analysis. Figure 3b shows the results given in Fig. 3a,
processed in this manner in the coordinate system $F - \delta$. They illustrate the
dependence $\delta = f(F)$, for the first loading cycle of the tested system, after its

assembly. Figures 3c, d show the characteristics of the deformations $\delta(t)$ for the third loading cycle of the given force $F(t)$.

The study shows (Fig. 3) that linear load runs $F(t)$ cause clearly nonlinear deformation runs $\delta(t)$. During the first loading of the investigated system deformations are elastic-plastic. At the second and subsequent loadings, not exceeding the previous maximum value, deformations are generally elastic. This is clearly shown by the measurement results presented in Fig. 3c,d, obtained for the third cycle of the same loads as in Fig. 3a,b.
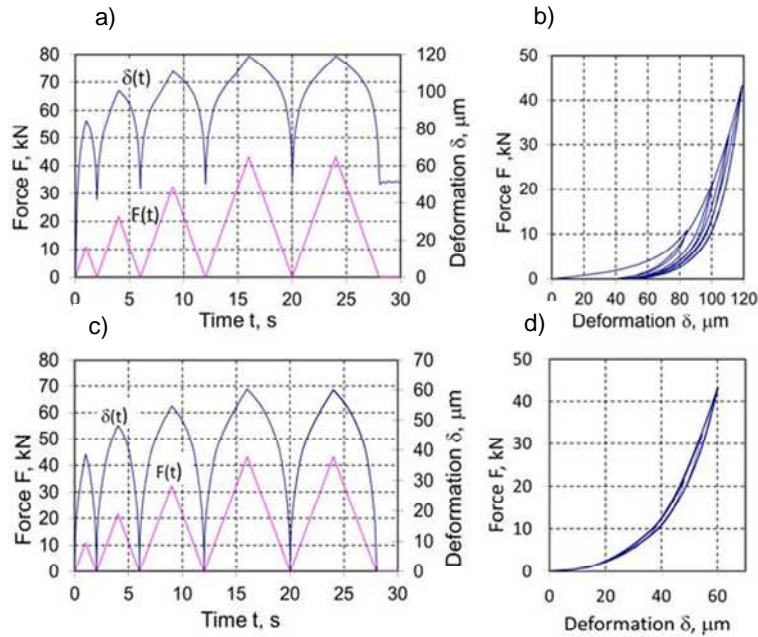

Fig 3. The characteristics of deformations $\delta(t)$ for the investigated system with
the chock with a nominal height of 34 mm determined in the first (a, b)
and third (c, d) loading cycle of the force $F(t)$

Small plastic deformations, taking place in the investigated system at the first loading process with an increasing force, can be explained by plastic deformations occurring at the tops of the roughness of the interacting surfaces of the system [12, 13]. These deformations can sometimes be important during the assembly of structural joints of accurate machinery and equipment. On the other hand elastic deformations occurring in this type of connections, often called "rigid connections", clearly show that they are not perfectly stiff. They explain the complex vibrations that occur frequently in such connections. These

deformations have often a significant influence on the flexibility of the whole system and must be taken into account in its modeling and static and dynamic analysis. This applies in particular to the analysis of vibration occurring in large reciprocating compressors systems, where the fastening systems are usually the weakest links of the whole systems [9].

The test results presented above refer to the nominal height of the tested chock, H = 34 mm. Because the chock's height is adjustable, measurements of its deformations were also carried out at the lowest and highest height (as defined in the company's catalogue [11]), that is, for 30 and 38 mm, respectively. The results of these measurements are shown in Fig. 4. They concern the system stabilized by several cycles of such loads, conducted after adjusting their height. The obtained deformation characteristics for these cases do not differ in terms of quality, but show some minor quantitative differences. These differences have no practical significance.
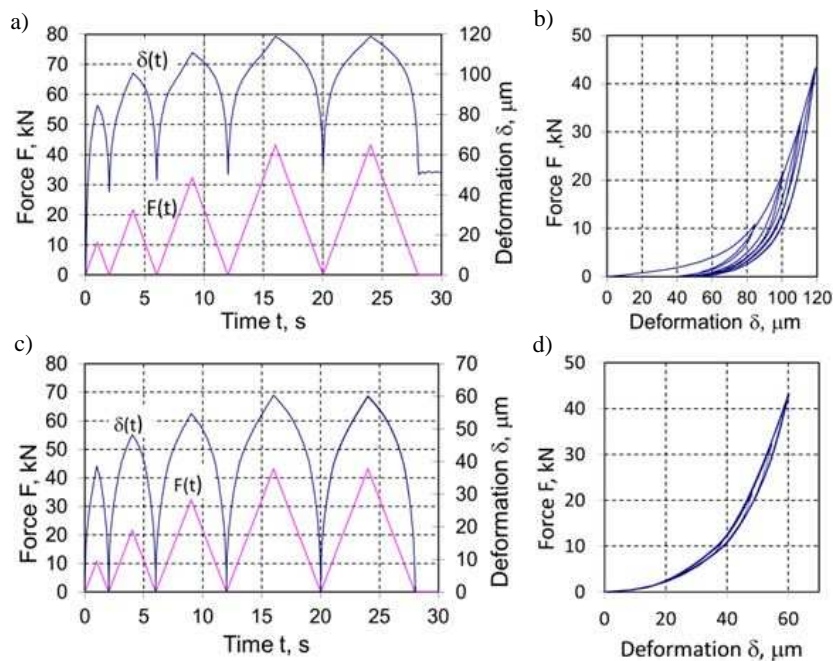

Fig. 4. The stabilized characteristics of deformations $\delta(t)$ determined for the investigated system with the chock at the minimum height of 30 mm (a, b) and at the maximum height of 38 mm (c, d)

Figure 5 shows the results of another experiment, performed with a linearly varying load over time. The test system was loaded by an increasing force and unloaded gradually, while the unloading was only partial. The time runs of the

applied load $F(t)$ and the deformation $\delta(t)$ caused by this load are shown in Fig. 5a, and the processed results of this experiment, in the coordinate system $F - \delta$, are shown in Fig. 5b. This relationship applies to a stabilized system. The deformation of the tested system increases in a continuous and smooth manner (Fig. 5b), despite a partial unloading which appears in the meantime. During the unloading and re-loading to the previous value, there is a clear deviation of the dependency from the main loading curve and consequently a hysteresis loop is formed. It depends on the level of the load, after which the unloading follows. When the re-loading force is reaching its previous value, a further increase in deformation follows the curve, which characterizes the deformations by a continuous steady increase of the load acting on the given system. The unloading curve for the system (measured by the total unloading) does not coincide with the loading curve. They form a fairly large hysteresis loop. The deformations of the tested system are elastic, and they disappear completely and immediately after its unloading.
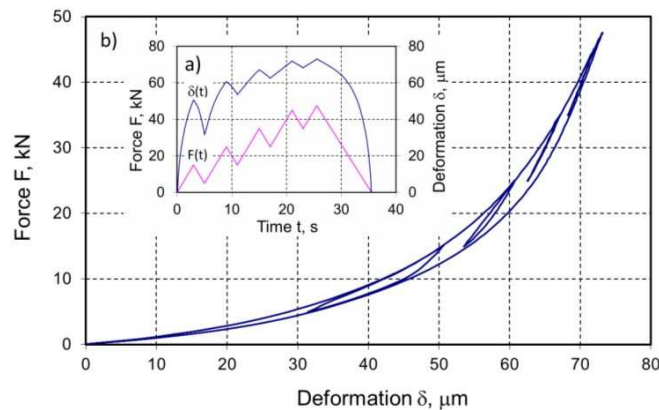

Fig. 5. Time runs of a linearly varying loading force and the deformations
caused by it (a) and the dependence of deformations on force (b), determined
for the investigated system with a chock with the nominal height of 34 mm

Figure 6a shows the time runs of a sinusoidally changing force $F(t)$ and the deformation $\delta(t)$ caused by it. Figure 6b shows the same measurement results, processed by computer which demonstrate the dependence of the deformation as a function of force, $\delta = f(F)$. They concern the chock with a nominal height $H = 34$ mm, after its stabilization by several cycles of such loading. The deformations caused by the given loads are elastic and clearly nonlinear. This means that for harmonic (sinusoidal) excitations, the deformation runs show a considerable deviation from the sinusoidal runs. They are characterized by

a lack of symmetry of the equilibrium rest position. The lack of symmetry is clearly visible at lower mean values and higher amplitudes of the excitation force.
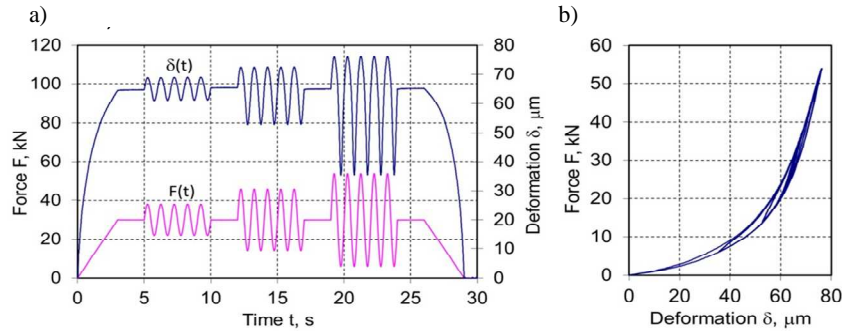

Fig. 6. Time runs of a sinusoidally varying loading force and the deformations caused by it (a) and the dependence of deformations on force (b), determined for the system with a chock with a nominal height of 34 mm

The non-linearity of the studied system is clearly visible in Fig. 6b. Its flexibility depends significantly on the current load and decreases with its growth. At cyclic loads hysteresis loops are clearly visible, showing the vibration energy dissipation. The measure of energy dissipated in one cycle of vibration is the field contained within the hysteresis loop. This energy can be determined by numerical integration of the following relationship

$$W = \oint F(\delta)\mathrm{d}\delta,$$

where $\oint$ denotes the integral of a closed circuit forming a hysteresis loop.
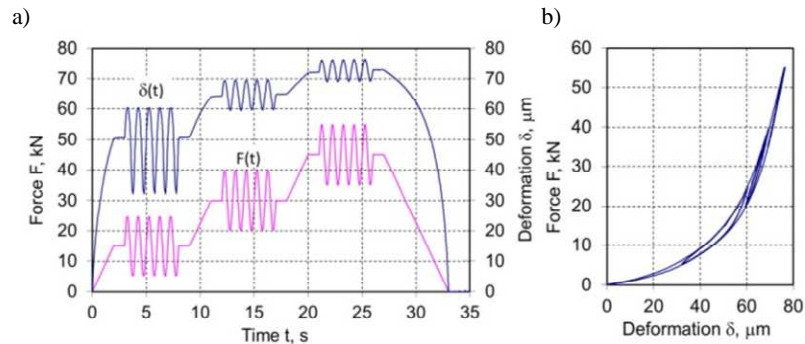

Fig. 7. Time runs of a sinusoidally varying loading force with constant amplitude and the deformation caused by it (a) and the dependence of deformations on force (b) for investigated system

Figure 7 illustrates the effect of the average load, for sinusoidal changing loads with a constant amplitude, on the deformation of the investigated system. A large quantitative and qualitative dependence of the load average on the vibration can be clearly seen. This also applies to the hysteresis loop (Fig. 7b). This is closely connected with a change of flexibility of the system. The smaller is the average load, at the fixed amplitude of the excitation force, the greater are the inclinations of vibrations and hysteresis loops. Under such conditions, the occurring nonlinearity of the studied system plays a particularly important role, in both theoretical and practical aspects.
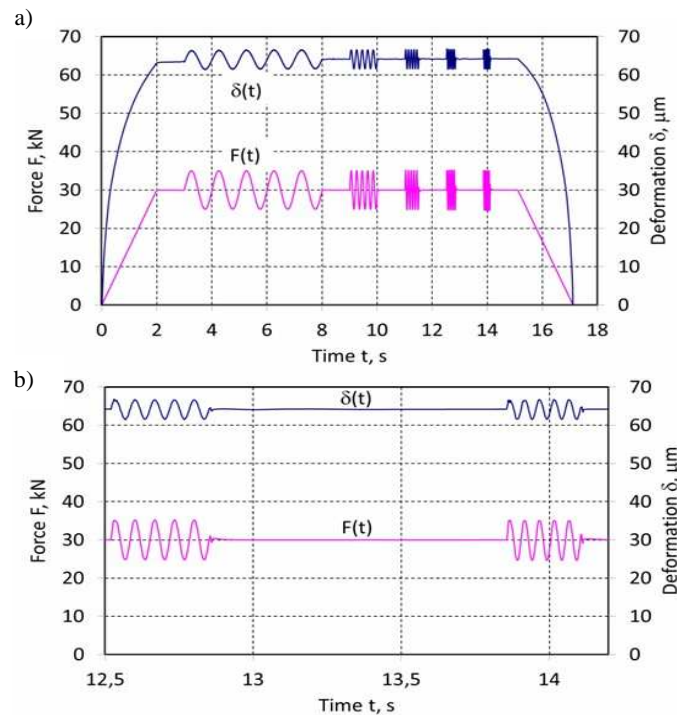

Fig. 8. Characteristics for selected sinusoidal loads with different frequencies and deformations caused by them in the investigated system; (Fig. 8b is a part of Fig. 8a in an enlarged time scale)

Figure 8a shows the time runs of a sinusoidal load $F(t)$ for frequency $f = 1$, 5, 10, 15 and 20 Hz, and the deformations $\delta(t)$ caused by it, and in Fig. 8b – a passage from this figure, in an enlarged time scale. The obtained graphs show a very good implementation of the assumed sinusoidal loads and high clarity and good repeatability of the results of strain measurements (with an amplitude of about 2 μm), in the examined frequency range. These studies showed that the

range of strain for all the specified excitation frequency is practically identical, which means that the flexibility of this system is independent of the excitation frequency values (in the investigated range of variation, feasible to be obtained on the used machine).

Conclusions

Results of the experimental studies presented in this paper have shown that in the steel adjustable foundation chocks Vibracon$^{®}$ SM, which are used in the so-called rigid seatings (mountings) on foundations of heavy machinery and equipment, there are significant non-linear-elastic deformations and hysteresis loops. An omission of these facts and treating such chocks and seatings (mounts) as perfectly stiff is a rather large simplification of reality, which is often the case in modeling and analysis of strength and vibration of such systems.

The obtained results confirm the already quite well known facts, that in the so-called. rigid structural connections, especially in bolted connections of machines and foundations, there are complex phenomena of frictional, vibration and strength nature. These phenomena have often a significant influence not only on the quality and durability of the mounting, but also on the behavior of the whole system in terms of its operation. Reference examples of such situation are large reciprocating compressors, operating in natural gas compressor stations, chemical industry and other technical fields.

Studies presented in this paper represent a part of an extensive research work, aimed at more detailed understanding of complex physical phenomena occurring in the so-called rigid seatings (mountings) of heavy machinery and equipment on foundations, and taking them proper into account in modeling and analysis of strength and vibration of these objects. The research work is carried out within a research project, which is conducted in close connection with practical activities, especially for ship machinery and equipment and large reciprocating compressors.

Acknowledgements

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