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VIBROACOUSTIC ACTIVITY OF MODERN HOIST MACHINES IN PASSENGER LIFT INSTALLATIONS

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The study investigates the sound levels registered inside the apartments in residential buildings resulting from the operation of the passenger lift installations. Modern multi-family residential buildings are typically equipped with machine room-less (MRL) passenger lift installations where the drive units are mounted directly on the shaft walls. Noise and vibration of the passenger lift operation has now become a major concern. Errors in engineering designs can lead to elevated noise levels in residences, particularly those adjacent to the lift equipment.

Subsequently, this may result in exceeding the permissible values of noise level, also vibrations in the apartments. Exceeding the permissible values of vibration and noise level on the one hand is a problem for users of residential premises, and on the other hand, it has an economic dimension, because the improvement of irregularities is often very expensive and financially burdens the developer.

This paper summarizes the results of studies highlighting the problem of elevated sound levels in residential areas adjacent to the shaft. The measurements of vibrations and noise in the apartment, as well as in the elevator shaft, showed that the vibroacoustic (V-A) signal is transmitted from the device to the flat. Spectral analysis and signal variability in the time domain were used. As part of corrective actions, mitigation measures and vibration isolation strategies have been proposed, however, not all proposals were feasible. Measurement results obtained prior to and following the vibroacoustic adaptation are compared in the context of noise and vibration control.

Keywords: passenger lift, noise, vibration, residential buildings, vibro-acoustic (V-A) adaptation.

Introduction

Elevated sound and vibration levels have now become a major concern, not only in the aspect of industrial noise or that caused by road traffic in the urban environment. The impacts of elevated sound levels, though with smaller amplitudes than industrial noise, are experienced by residents in their homes and that is exactly where people expect to find peace and quiet. It is not that everybody can well afford to buy their own house, in a locality far distant from busy roads or major industrial plants. An apartment in a multi-family residential building is, therefore, the popular alternative. Apartments in newly erected buildings are usually rather expensive, partly due to high costs of land. That is why developers make special efforts to reduce the prices of apartments offered for sale while demonstrating compliance with the engineering practice requirements. However, there remain other significant issues related to residents' comfort, particularly in the context of noise levels.

Major determinants of acoustic comfort are [1]:

- actual location of the building on the plot of land, taking into account the external sources of acoustic disturbances,
- division of the building into acoustic zones,
- choice of building materials and structural design,
- selection of partitions and insulation and sealing of ductwork,
- eliminating the disturbances caused by the machinery and equipment inside the building.

In many cases the latter aspect is of primary concern and the residents' comfort is thus threatened.

Modern machinery and equipment in today's buildings have now become the necessary components and, at the first glance, a major factor in assessment of the apartment quality category and standard. The equipment provided in most buildings includes air-conditioners, fans, energy-recovery systems and passengers lifts. When the machines and equipment are not well-chosen for the given application (having the incorrect vibro-acoustic parameters, i.e. generate too high sound power levels) or ineptly installed (lack of vibro-isolation or badly-chosen vibro-isolation technique), residents are likely to experience adverse impacts from noise and vibration, reducing their comfort. It can also lead to deterioration of functional (acoustic) features of public buildings, such as cinemas or theatre halls, lecture rooms and the like. Recently, research work has been undertaken to investigate the effects of background noise on broadly-understood functional (acoustic) features of the buildings interior. This issue was addressed in more detail in the work [2].

Passenger lifts are those building components which present the potential for intrusive noise and vibration to residents. Lifts installed in modern buildings are mostly gearless traction machines with drive units mounted directly on the shaft walls. Older lifts had their drives mounted in machine rooms on top of the shaft, on a supporting structure. It is quite common that shaft walls in buildings abut on the walls in the apartment, despite current guidelines recommending that some space should be left in between. Vibrations of the drive unit are transmitted via the supporting structure to the apartments, where they can be sensed by the residents. Even though some vibration insulation is usually provided between the drive unit and the supporting structure, this vibro-adaptation method often proves inadequate. Further sources of noise and vibration include: opening and closing of the lift car doors, sound signals and vocal announcements, sound of lift ride (vibration of hoisting ropes, noise produced when car elements and guides are in contact). Most sounds and vibration permeating to the apartments could be eliminated provided that building walls are properly designed. The wall structure in the aspect of the transmission loss (TL) should be considered already at the design stage, both the walls of the building and the cabin of the passenger lift [3]. The shape of the room is also important, because of its acoustic parameters which have to be taken into account [2, 4]. Actually, design and construction errors are responsible for a variety of adverse impacts.

There are numerous reports addressing the problem of noise and vibration due to operation of passenger lifts in residential buildings. In the work [5], the author summarizes the criteria for assessing the vibration and acoustic performance of lifts and identifies potential sources of noise due to the operation and constructional features of lifts, observing that passenger lifts in residential buildings present the potential for intrusive noise and vibration to the dwelling units. The adverse noise and vibration can result from the passenger lift equipment located in the machine rooms or the shafts. The impacts can be significant issues related to sound quality, sleeping conditions and enjoyment within residences [5]. According to the data contained in [5], it should be added that some countries have no criteria regarding noise from elevators (for example South Korea [6]).

In work [5], it was pointed out that one of the reasons for the high V-A activity of passenger lifts is the use of hydraulic drives. When specifying the issue, the reason for excessive vibrations and noise of hydraulic drives should be mentioned, among others pressure pulsation in hydraulic pipes and general hydraulic pumps noise, more widely discussed in [7–9].

The issues related to the impacts of lift operation in residential buildings are investigated in [10]. According to the authors, in the case of modern machine-room less (MRL) installations, the lift machinery is mounted inside the lift's shaft and directly or indirectly on the shaft wall. In many cases living quarters or bedrooms are located behind this wall, which results in residents' discomfort. The authors observed that even though the admissible noise levels specified in respective building standards and codes have not been exceeded, the residents still complain about the noise produced by the drive mechanism. The authors of [10] concluded that in the majority of the researched lifts the noise in the apartments is due to structure-borne sounds.

Measured noise levels inside buildings where the major source of noise was a passenger lift operation are collated in [11]. Measurements were taken at selected points inside the buildings, one of these buildings being old, the other-new. In the case of the new building, the effects of acoustic adaptation were obvious. The authors of [11] mention the impacts of roller noise and observe that in office buildings, roller noise is not perceived as a problem at all. However, in residential buildings, lift noise in bedrooms abutting on the lift shaft is a major concern. The authors did not mention the lift type, yet it is reasonable to suppose that measurements were taken in a building equipped with a lift installation with the machine room located on top of the shaft.

In order to effectively reduce the sound levels and vibration caused by lift operation, the performance of its individual components has to be considered. A major source of noise is the drive unit, and its operation can be sensed by the residents. The authors of [12] investigated a prototype of a gearless drive, identified the causes of low-frequency vibrations and suggested a modification enabling the drive vibration to be effectively reduced.

Research into the noise level reduction of the lift drive were also presented in [13, 14]. The authors concluded that, the design of a low-noise motor for all purposes must begin with the selection of key geometrical active-zone ratios (the number of stator and rotor teeth, the shape and size of slots, slot skews, air gap, etc.) and electromagnetic loads.

The work [15, 16] summarizes the results of research efforts focusing on the diagnostics of the drive unit installed in the upper engine room of the lift. The authors came to the conclusion that technical condition assessment of the passenger lift gear on the basis of amplitude and nature of vibration would be possible only when a diagnostic model were available which well captured the vibration of the new device.

In the literature, one can find works on modeling in the aspect of the work of passenger lifts and their components (including vibrations of lift ropes, vibrations of buildings caused by cranes, vibration of the drive, the impact of the lift work on the noise level in the room) [17–20].

Obviously, the problem of noise and vibration caused by lift operation is well-known and extensively studied. It is worthwhile to mention, though, that the problem is not restricted to the lift installations themselves (as long as they do not get damaged and the noise and vibration are associated with routine lift operations exclusively), the major concern are people who experience their adverse impacts [21].

This study investigates the adverse noise and vibration impacts of hoist machine operation in a modern, machine-room-less passenger lift. The main objective was to highlight how implementation of selected lift design solutions (vibration isolation, spacing of elements supporting the car guides) should impact on the sound level and vibration inside a selected apartment adjacent to the lift shaft wall. Measurements were taken of sound levels and vibration generated by the lift drive and those registered inside the apartments.

Technical specifications of the hoist unit are not provided because the study did not aim to evaluate the performance of the given hoist model, the main objective was to highlight the impacts of individual components of the test object.

1. Test object

The analysed object was a passenger lift in a multistorey residential building and the main purpose of the monitoring program was to develop an effective acoustic and vibro-adaptation strategy. Sound level measurements taken in one of the apartments revealed that admissible sound levels specified in [22] were exceeded in two rooms within the apartment (located on the top storey). The walls in rooms in which elevated sound levels were registered directly abutted on the shaft wall. The layout of the investigated apartment is shown in Fig. 1.

The lift in the building is a machine-room less, electric-drive gearless installation (Fig. 2). The car is suspended on 6 ropes and travels on guides fixed on the shaft walls, the counterweight moves upon the guide rails. The drive system is located on the shaft top (above the top storey). The driving motor is mounted on the same wall as Room No 1 and on the same lev-

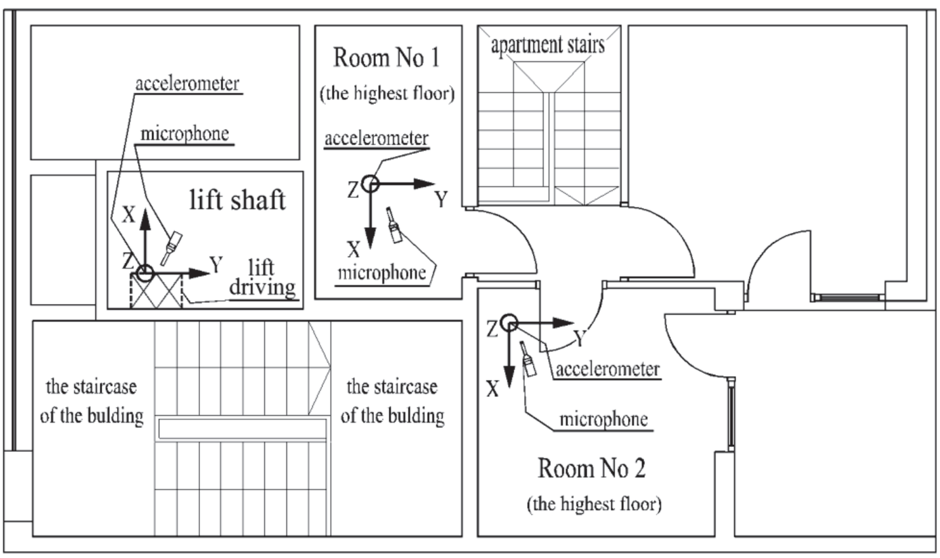

Fig. 1. View of the apartment

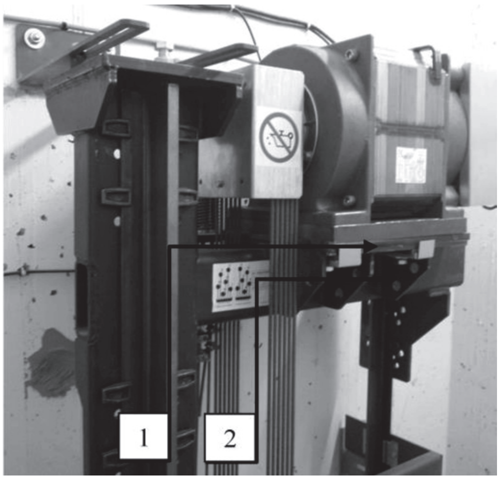

Fig. 2. The analyzed lift drive

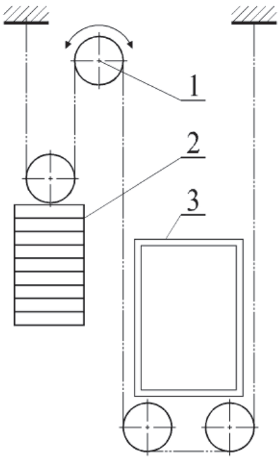

Fig. 3. Roping system of the analyzed lift

el (Fig. 1). The schematic diagram of the roping system is shown in Fig. 3. The drive unit is bolted to steel support via a vibro-isolating element (Fig. 2).

Apparently, the lift operation gives rise to excessive noise levels in the apartment being analysed. Measurements were taken to identify the levels of sound and vibration energy transmitted into the apartment and selected results are summarized in further sections.

1.1. Vibro-acoustic adaptation of the lift installation

The design structure of the passenger lift was analysed to identify those components that have potential to generate sound and vibration energy and to locate the transmission paths where noise and vibration penetrate the residential units. The analysis highlighted the structural components to be adapted such that the sound and vibration levels inside the apartments should be reduced. Actually, very few components were found to be adaptable. The analysis was further extended to investigate the potential effects of vibration isolation of the drive unit, of the manner in which the guide rails are fixed to the shaft walls and the vibro-acoustic performance of a hoist unit (examined hoist units were of the same type). Next, measurements were taken to determine how implementation of the proposed vibro-acoustic adaptation strategies should affect the sound and vibration levels in one of the apartments.

2. Measurement procedure

The procedure, outlined below, involved several sessions of measurements. Sound levels and vibration accelerations were measured inside the apartment in order to identify the incoming acoustic and vibration signals. The measuring equipment consisted of a four-channel spectrum analyzer Svantek SVAN 958. Depending on the actual configuration, the following features were available:

– accelerometer Svantek SVAN 207A (a triaxial sensor), for measurements of vibrations inside the apartment;
– accelerometer VIS-311A (sensors arrayed perpendicular to one another), for measurements of the drive vibrations
– a microphone ½”, for measurements of noise of the drive and inside the apartment.

2.1. Methodology of the hoist noise and vibration measurements in the shaft

Measurements of sound level and vibration generated by the passenger lift were taken in the shaft so as to identify the characteristic frequencies in the system operation. The frequency identification procedure, in aspect V-A activity of drive unit, was also made in the apartment.

Vibration levels were registered by accelerometers positioned on the drive frame (Fig. 4) and on the steel support (Fig. 5), to determine the effectiveness of the applied vibration isolation. Throughout the measurement procedure the drive system operated under no-load conditions, with ropes disengaged from the sheave. The locations of measurement points in the shaft with indicated axes are shown in Fig. 1.

Noise measurements were taken with a microphone located directly by the lift drive, under no-load conditions. Registered parameters included the vibration and acoustic signal amplitudes and their variations in time, the sampling frequency being 12 kHz. Vibration measurements were taken in three axes, afterwards the acoustic and vibration signals were processed using the dedicated signal processing software SvanPC++.

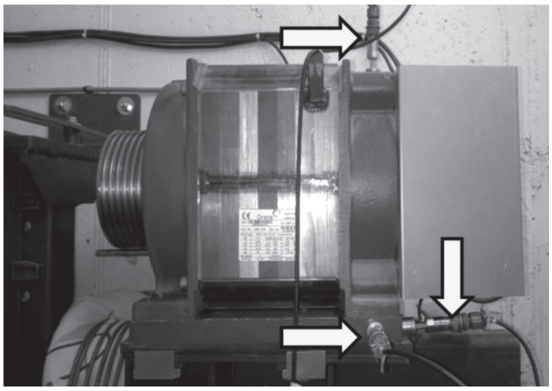

Fig. 4. Sensor positions on the drive unit

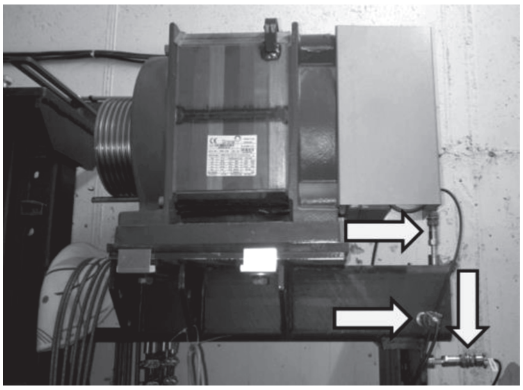

Fig. 5. Sensor positions on the steel support

2.2. Methodology of sound level and vibration measurements inside the apartments

Sound and vibration level measurements were taken in the living quarters to identify frequencies transmitted into the apartment. Similar to the procedure applied during measurements in the shaft, the registered parameters included the amplitudes of vibration and acoustic signals and their variations in time (with the sampling frequency 12 kHz). Vibration signals registered in three axes were processed using the dedicated software SvanPC++.

The actual locations of measurement points inside the apartment are shown in Fig. 1.

3. Measurement results

Selected measurement data are summarized and discussed in further sections, with the main focus on comparison of results obtained in the shaft and inside the apartment.

3.1. Sound levels and vibration of the hoist machine measured in the shaft – prior to the V-A adaptation

Fig. 6 summarizes the results of the hoist vibration measurements in the initial conditions, i.e. prior to the vibro-adaptation program. Fig. 6a illustrates

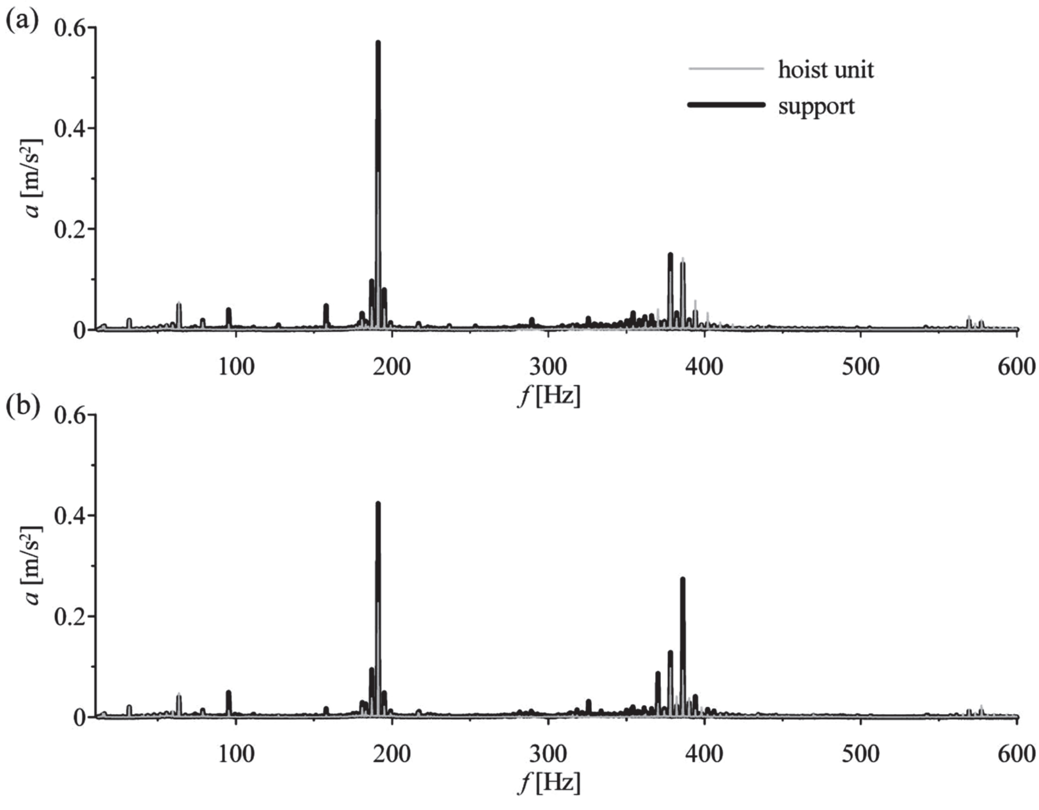

Fig. 6. Vibrations of the hoist unit prior to V-A adaptation

(a) – upward travel, (b) – downward travel

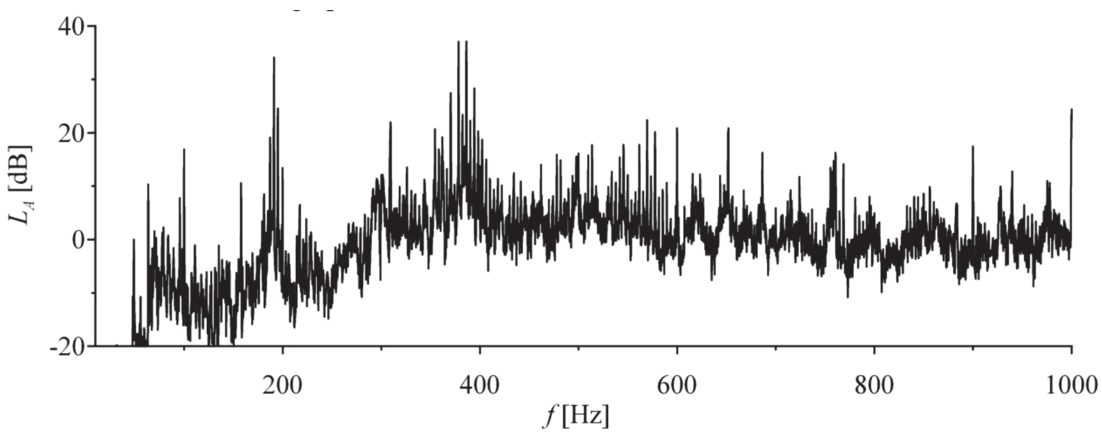

Fig. 7. Sound levels due to the hoist unit operation prior to the V-A adaptation- identification of frequency components

the case of the drive being operational during the upward travel of the lift, Fig. 6b captures the conditions during the downward travel.

Results clearly indicate that the drive vibration energy tends to concentrate in narrow frequency ranges, associated with the rotating motion of the drive system (motor, gears). The predominant frequency component is found to be 191 Hz, the next significant components have the frequency nearly twice as high (about 380 Hz). Amplitudes of the remaining components are decidedly lower. Comparison of vibration amplitudes registered on the hoist unit and on its support is suggestive of considerable vibration transmission performance despite the use of vibro-adaptation. The steel support is attached to the shaft wall with no vibration insulation provided, hence its vibrations can be easily transmitted onto the reinforced concrete elements making up the shaft construction.

Fig. 7 collates the sound level monitoring data obtained in the shaft (using a microphone placed directly by the drive). Their analysis reveals the main frequency components associated with rotation of the driving system. The total sound level registered in the shaft whilst the lift is moving is of the order of 58 dB. For the given shaft wall thickness (about 15 cm) and the estimated transmission loss TL= ca. 40 dB, the air-borne sound transmission from the shaft to the apartment should be of little significance.

3.2. Vibration and sound levels registered inside the apartment

Fig. 8 plots the results obtained in Room No 1.

Spectral analyses of vibrations and sound pressure have confirmed the large proportion of frequency components associated with the drive operation (fre-

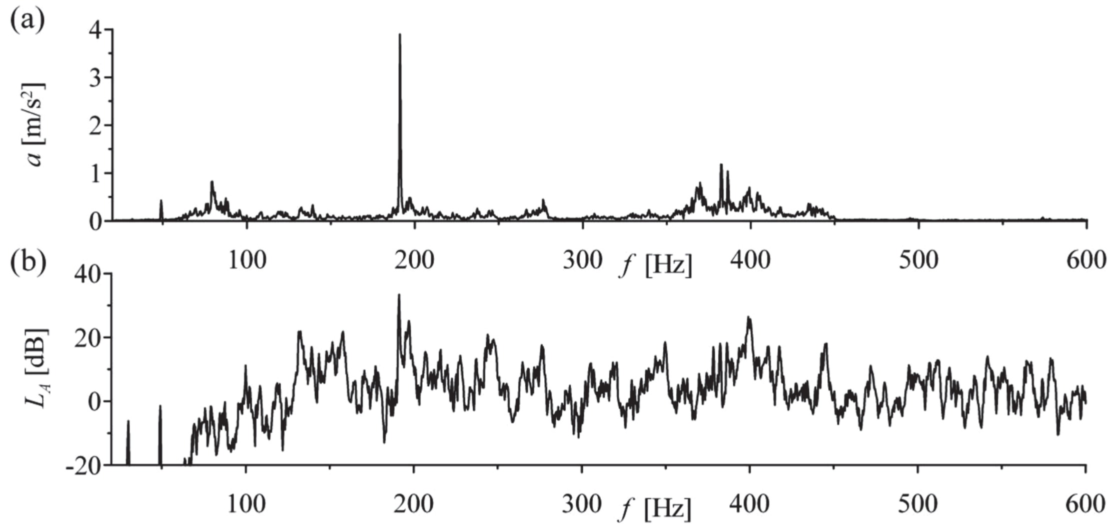

Fig. 8. Frequency components of sounds and vibrations in Room No 1- prior to the V-A adaptation
(a) – acceleration values, (b) – sound level values

quency component ca 190 Hz) in signals registered inside the apartment (Fig. 8a and 8b). Apart from these, there are other frequency components associated with the phenomena induced by the movements of the car, counterweights and the roping system.

Sound level and vibration data registered throughout the full duty cycle of the passenger lift indicate that apart from previously listed acoustic and vibration phenomena associated with drive operation, movements of the car and counterweights, the registered signals (particularly acoustic signals) reveal the impacts of other lift sub-assemblies being operational (for example the brake release mechanism). The sound levels throughout the full duty cycle of the passenger lift, registered in Room No 1, are shown in Fig. 9.

3.3. Measurements of the drive vibrations-effectiveness of vibration isolation

Results of measurements taken to validate the adequacy of the applied vibration isolation between the drive unit and the steel support are collated in Fig. 10. Data collected when original vibration insulation only was provided (dark lines) are duly compared with those obtained for the modified vibration isolation and V-A adaptation suggested by the authors (bright lines). The vibro-isolator was replaced by one of the same type. Fig. 10a plots the vibration isolation characteristic in the X axis, Fig. 10b – in the Y axis and Fig. 10c – in the Z axis. It is worthwhile to mention that the authors were not acquainted with the full damping characteristics of the original and modified vibration isolation system.

Plots in Fig. 10 were obtained by comparing the amplitudes measured on the hoist support and on the hoist unit. The dumping coefficient K is defined as (1):

$$K = \frac{a_{support}}{a_{drive}} \quad [-] \tag{1}$$

where: $a_{support}$ – acceleration values measured on the steel support, a_{drive} – acceleration values measured on the drive.

The value of K=1 indicates the identical vibration amplitudes registered in the drive and the steel support (identical accelerations registered on the drive and on the support), K less than 1 indicates lower vibration accelerations registered on the support than on the drive (attenuation of vibration) and K in excess of 1 (enhanced vibration) indicates that steel support vibration accelerations are larger than those registered on the hoist unit. The plots are given of vibrations measured in three axes. Dark lines represent the results prior to the V-A adaptation, bright lines give the results obtained for the modified vibration isolation system. Apparently, in the range of dominant frequency components of the hoist vibration (ca 200 Hz, ca 400 Hz) the performance of the vibration isolation system is found inadequate and in a large extent vibrations are transmitted from the hoist upon the steel support. There are differences in vibration isolation performance levels registered in three axes, yet in general it can be considered as low-quality. In fact, modification of the vibration isolation system has resulted in a slight improvement of the vibration isolation performance in the Y axis only.

3.4. Comparison of vibration spectra for the same type of hoist units

Selected spectra obtained for the same model of the hoist units are shown in Fig. 11. Fig. 11a shows the vibration spectrum obtained for the hoist unit originally mounted, Fig. 11b – for the hoist unit after replacing with a new one.

Apparently (see Fig. 11), the frequency spectra follow the similar pattern (revealing the dominating frequencies ca 200 Hz, 400 Hz). After the modification (after replacing with a new one), the acceleration amplitude could be reduced by 10 dB.

4. Comparison of vibration and sound levels in the analySed rooms-effects of V-A adaptation

The acoustic adaptation measures that were put in place included the replacement of vibro-insulating

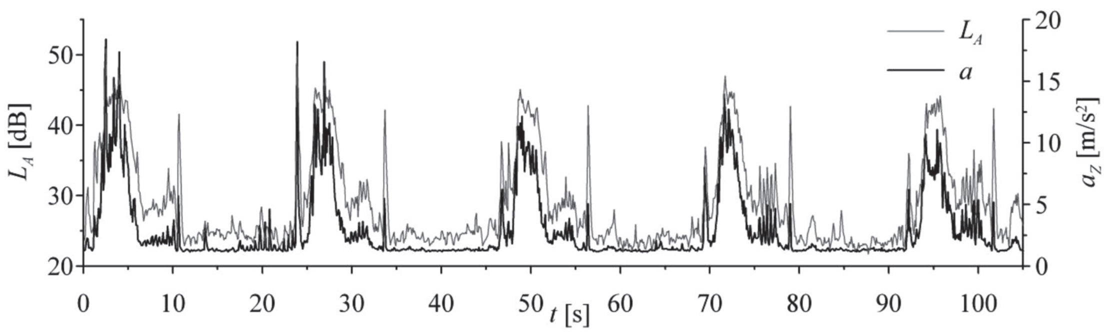

Fig. 9. Full duty cycle of the passenger lift- downward travel, registered in Room No 1

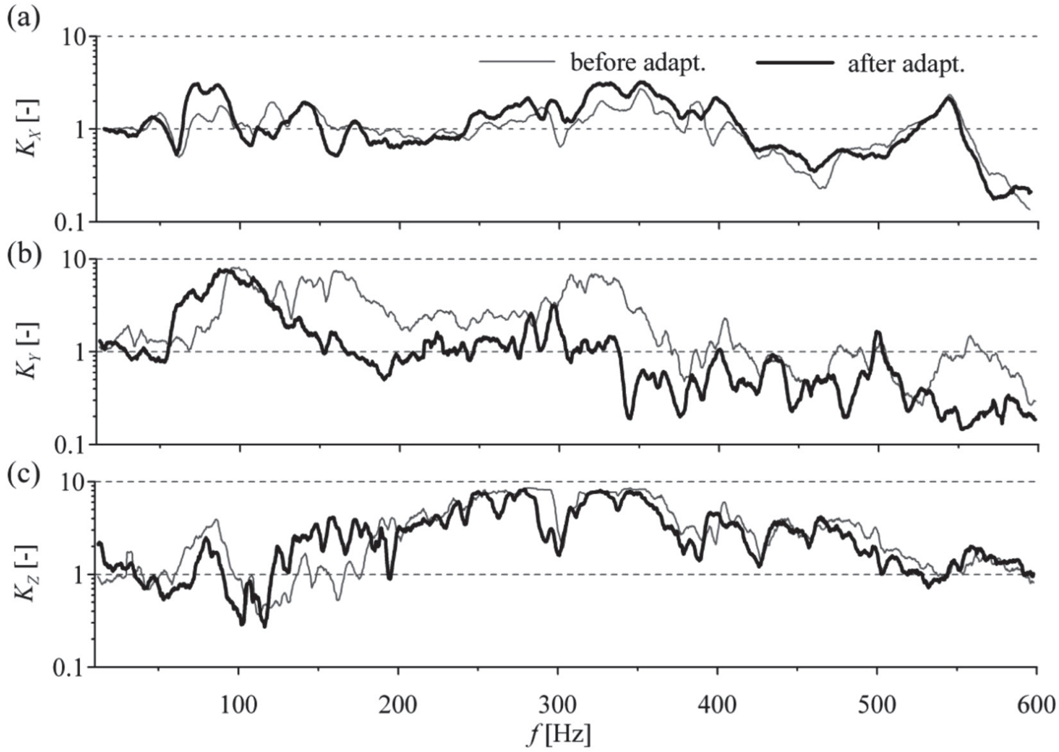

Fig. 10. The dumping coefficient K in the function of frequency in the case of modified vibration isolation of the drive

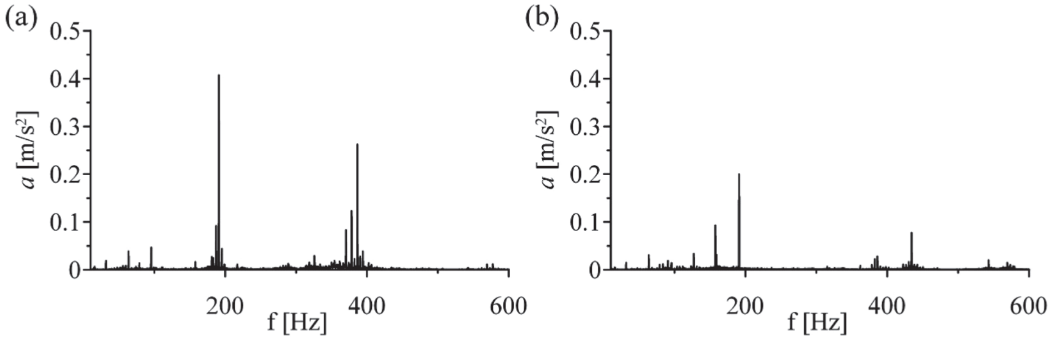

Fig. 11. Comparison of results obtained for two hoist units of the same type

(a) – original hoist unit; (b) – hoist unit after replacing with a new one

spacers, changing the spacing of the guide rail attachments on the shaft wall (originally the supports were mounted at mid-length between floor slabs on two neighbouring floor levels). After the adaptation program, the supports were mounted in the proximity of floor slabs, which reduced the vibration of the shaft walls. The overall results of the adaptation program are illustrated in Fig. 12.

Modifications to the system (replacement of the vibro-isolating elements, altered spacing between guide rail attachments) resulted in the vibration reduction in the range of 190 Hz at all analysed localities. As regards noise level, these components could be reduced in Room No 2 only.

Summary

Vibration and sound level monitoring indicate that vibro-adaptation of the lift drive and its infrastructure have resulted in reduction of vibration and sound levels in analysed rooms. Modifications to the system have resulted in a slight improvement as the sound level in Room No 1 was reduced by ca 1 dB whilst that registered in Room No 2 remained unchanged. Modifications have resulted in vibration reduction in the analysed rooms, by 0,9 dB to 3,0 dB. Vibration reduction has proved more significant than sound level reduction, which indicates the major contribution of airborne noise. In consideration of the fact that predicted

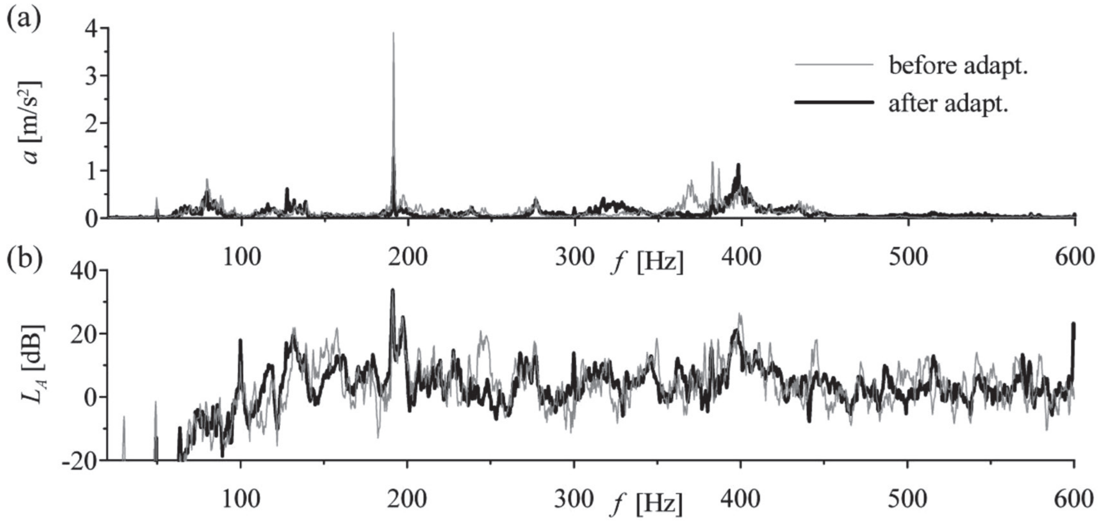

Fig. 12. Frequency analysis of sounds and vibration in Room No 1 after V-A adaptation
(a) – acceleration values, (b) – sound level values

Table 1

Sound levels L_A and acceleration values registered in analysed rooms prior to and after vibro-adaptation measures in the lift shaft

Location of measurement point (Fig. 1)	Test conditions	Sound level reduction ΔL_A [dB]	Vibration amplitude reduction *Da* [dB]
Room No 1	Upward travel of the car	1,0	0,9
Room No 1	Downward of the car	1,3	2,0
Room No 2	Upward travel of the car	–0,2	3,0
Room No 2	Downward travel of the car	–0,1	1,3

transmission loss value for the wall made of reinforced concrete is rather high, it would be reasonable to check other sound transmission paths, such as unidentified ductworks or dilatations. Analyses of vibration spectra and sound pressure levels evidence the major contribution of frequency components associated with the drive unit operation (ca 190 Hz). V-A adaptation of the system has led to vibration reduction in the frequency range 190 Hz at all analysed sites, whilst in the case of noise control, the sound level reduction in this frequency range was registered only in Room No 2. Vibration and sound levels analysis covering the full duty cycle of the lift operation reveals that alongside vibroacoustic phenomena associated with the drive operation, the registered signals (acoustic signals in particular) embrace the impacts of other lift sub-assemblies and their operation (for example brake release mechanisms). Consequently, the comparative analysis of sound and vibration signals from a variety of drive mechanisms seems fully merited. In the case investigated in this study, sound levels registered for several hoist machines of the same type were found to differ considerably.

This paper presents the results of measurements and analyzes for the whole system, which is a residential building with a passenger lift system. Elements that were analyzed were selected based on a literature review [10–16]. Lack of access to the documentation of the system also have not allowed for the implementation of numerical calculations. Information contained in papers [3, 4, 17–20] allows to select those elements of the system, which should be subjected to simulation calculations, especially in the context of vibroinsulation and sound insulation.

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