Mechanical reaction of the frontal abdominal wall to the impact load during gravidity

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Submitted: October 20, 2002
Accepted: November 9, 2002

Key words: gravidity; impact load; vibration; cinematographic method; tensometric method

Abstract


METHOD: Damped vibration of the gravid abdomen was detected after a defined impact load using speed cinematographic recording of 103 pictures/sec. A woman in 32nd week of gestation, performing toe stand and fall down to the heel, the drop was 0.08 m. The recording was digitalized and the values mathematically analysed. The method used was PAM (polynomial approximation method) of approximation of discrete coordinates. The umbilicus’ trajectory in reaction to the impact load was described analytically and interpreted graphically. Parameters of abdomen vibration were detected in horizontal profile by tensometric belt. Impact in interaction of soles with the underlay was detected with the help of tensometric platform Kistler. Ultimate strength point of myometrium was set by tearing experiment in 12 samples.

RESULTS: Calculation of characteristics of damped, aperiodic vibration of hydro-viscous elastic system as the outside behaviour of the gravid abdomen. Parameters in vertical direction of umbilicus: impulse in abdominal area – 2,72 Ns, T-period – 0.1299 s, amplitude – 0.009 m, frequency – 7,7 Hz, functional damping – from –6 to +12 Nsm⁻¹. In horizontal direction: frequency 5,4 Hz, damping 123 Nsm⁻¹. Impact in soles’ sphere 40 Ns with maximum value 1511 N, which represents level 2,2 G. Ultimate strength point of myometrium is 0,1 – 1,1 MPa.

CONCLUSION: The results show one of the possible critical, risky frequencies of the gravid abdomen, that is, in this concrete case, the frequency of the vibrating system of cca 7,7 Hz in vertical direction and cca 5,4 Hz horizontally. This implies that e.g. this frequency is dangerous (possible abruptio placentae) and is necessary to be avoided e.g. when travelling by means of public transportation. The applied analytic methods and presented parameters will be used for e.g. modelling the examined gravid system under impact load of a general character – locomotion, work-load, car accidents, etc.
Introduction

Gravidity represents system *sui generis*. Vibrations of a body and specially abdomen laparoseismicities are an everyday matter; they happen permanently. Oscillations are started as a result of present impulses. They are caused by inner factors – breathing waves, abdominal aorta, intestinal peristalsis, using abdominal press while pushing, coughing, sneezing, foetus movements in gravidity, uterus topic changes during contractions in childbirth. Outer factors – they impact with different power, in different direction during any motion, while walking, hopping, during coitus, during vibrations in the means of transportation and vibrations at work etc.

Apart from everyday impulses impact loads in traumatism play a special role. Impact load – abdominal vibrations (gravid uterus and topically related organs – GUTO) may as a consequence reach utero-placental connection itself. Practically the most significant role in various mechanical impact loads on gravid abdomen play traumatisms generally, especially in transport accidents, which is a serious world problem [1–6], and others.

During all given regimes vibrations take place that set abdomen, enlarged by pregnant uterus, vibrating. Uterus itself reaches high above naval at the end of gravidity, it is fixed backwards by sacral-uterus ligaments which form in the area of L4–L5 gravid retro-uterus space which is being used at the start of lower hollow vein syndrome and aorta-concave compression during childbirth [7]. Uterus oscillates as an upturned pendulum, in front it leans on muscles of frontal abdominal wall that absorbs vibrations.

The whole body reacts as an integral whole, every participating item, bones, ligaments, muscles, myometrium, connective tissue, membrane bag, amniotic fluid, placenta – is given mechanically different parameters of rigidity, stiffness, elasticity, density, damping. Tissue instability under impact is different, with supra-threshold impulses defects of its structures may appear which will call out chain of following reactions.

Within the frame of general problems of hydro-viscose vibrations and elastic systems we were solving the range of these vibrations and their consequences from the point of view of the followed complex damping [8, 9]. Abdomen enlarged by gravid uterus is a very complicated system from mechanical point of view. Uterus itself is fixed backwards by sacral-uterus ligaments which forms specific gravid retro-uterus space supported by frontal abdominal wall muscles. Uterus contains amniotic fluid, foetus and placenta, when each of these subsystems (i.e. placenta, amniotic fluid and abdominal muscles and individual tissues) have different mechanical qualities – elasticity, rigidity, stiffness, damping [2] etc.

In the process of our work we asked a following question: *What is the basic characteristics of abdominal vibrations after defined load*. Its answer is a prerequisite for further solution of problems connected with loading the pregnant women in current and extreme loads.

Method

For non-contact, non-invasive data recording of abdominal vibrations we used a method of speed cinematographic recording from lateral side projection in frequency 103 pictures/sec. Further we used tensometric belt that outlined abdomen in the biggest diameter and registered frequency changes in impact load. Both measurement systems were electronically synchronized and analysed separately. The third used synchronized method was dynamographic reaction recording of the underlay with the help of Kistler platform with possibility of 3D reaction power recording during interaction of soles and underlay.

The examined pregnant woman in the 32nd week was at first standing calmly on toes and then fell on extended legs by orders. The height of this “fall” was 0,08 m fig.1.

The first analysis was made from recorded vibrations of a pregnant abdomen taken in reference as umbilicus. Weights of all topically appropriate organs having substantial connection to vibrating pregnant abdomen refer to it. The umbilicus’ trajectory was added to the solution. Wakening impulse with short lasting where shape of impulse course could be neglected, had theoretical value 6.4 Ns max. Weight of vibrating abdomen was calculated by uterus with amniotic egg and topically appropriate organs at m = 5.1 kg. The model was considered as a complex of material point placed with the help of a spring and shock absorber in all three directions of the system of coordinates. Solution of dynamic qualities was made for vertical direction. Absorbing characteristics were shown this way. Discrete points of umbilicus y-coordinate were at first approximated by polynomial approximation method. From thus treated trajectory function course speed courses were analytically described – fig.2. – and acceleration. After setting appropriate values frequencies were counted, stiffness and proportionate damping of the vibrating point. Similarly vibrating parameters of gravid abdomen in horizontal plane were gained with the help of tensometric belt. Basic wakening parameters were detected by tensometric platform Kistler. Ultimate strength point of myometrium was set experimentally with twelve samples of transverse, lengthways and oblique sections.

Results

Cinematographic method

Umbilicus kinematics was being solved. Wakening impulse with short length of lasting, with possibility of neglecting the shape of impulse course and theoretical value max. 6.4 Ns. Weight of vibrating abdomen was m = 5,1 kg.

Four models were constructed for cinematic data. These models were made more and more precise and gradually represented models accepting more qualities of organisms in vivo. Gradually systems with free subcritical vibration of damped complex (pregnant abdomen) were modelled with one free grade. Further models then accept more the solution of characteristics
of strongly damped, aperiodic, overcritical
damped vibration of gravid uterus and top-
ically appropriate organs as a whole. Fur-
ther model is represented by the model of
supercritical constant damping. The last
model, the results of which we are present-
ing is represented by the model of vibrating
complex with damping parameter depend-
ing on actively changing damping (nonmo-
notonous functional dependence, Fig. 2.) –
which is biological reality of alive vibrating
system of gravid uterus and topically ap-
propriate organs.

They are active changes of also biologi-
cal parameters of appropriate tissues that
may be actively corrected depending on for
instance, perception and estimation of the
following situation under impact load
of a body in interaction with surround-
ings. The result of this model of a following
movement is a complex of directing equa-
tions like this:

\[ m\ddot{x} + b_0 + b_1 \dot{x} + b_2 \dot{x}^2 + \ldots + b_n \dot{x}^n \dot{x} + kx = 0 \]

The unknown is stiffness \( k \) and the sec-
ond unknown is a constant \( b \) by which
polynom of damping (depending on speed)
is multiplied. The solution leads to pre-
given complex of linear equations with two
unknowns.

**Fig. 2.** Speed and damping in model M3B for moving body GUTO \( m = 5.1 \text{ kg} \) for data from film recording.

First derivation of a trajectory-speed, after modi-

\[ \text{PAM} = v [\ \text{ms}^{-1}] \]

The course of active damping: active damping:

\[ -b [\ \text{Nsm}^{-1}] \]

Model M3B with active damping. Its course is approximated by polynom of
30.grade-similarly to the course of speed.

Stiffness of the complex: \( k = 302,4 \text{ Nm}^{-1} \)
Absorption of the complex: \( b = -6 \text{ to } 12 \text{ Nsm}^{-1} \) – functional dependence
(the sign means direction of damping)
Frequency of the complex itself: \( \Omega = 7,7 \text{ Hz} \).
**Tensometric method**

At first stiffness of the measuring belt was set with the help of dependence of deformation on extending strength to 0,37 Nmm\(^{-1}\). From the recording of measurement on tensometric belt Myodat fig.3, parameters of damped vibrations GUTO were counted in horizontal plate.

**Reaction of an underlay on tensometric platform Kistler**

The recording of the course of vertical interaction strength between underlay and a sole of a gravid woman is on fig. 4.

Frequency \(\Omega\), damping \(\xi\) and stiffness \(k\) of the system are derived from the relations for harmonically damped motion. Basic equation of this motion is:

\[
y(x)=v_0 \cdot e^{-\xi x} \cdot \sin \frac{x}{T}
\]

Parameters of the harmonic damped motion are:

- \(T\) ... time of one period (we read from recording)
- \(v_0, v_1\) ... following amplitudes of motion (we read from recording)

Frequency \(\Omega\) resp. coefficient of damping \(\xi\) derived from relations:

\[
\Omega = \frac{1}{T}, \quad v_i = v_0 \cdot e^{-\xi T}, \quad \xi = -\frac{1}{T} \cdot \ln \frac{v_i}{v_0}
\]

Stiffness of the system \(k\) is then:

\[
\Omega_B = \sqrt{\frac{k_B}{m_B}} \Rightarrow k_B = \Omega_B^2 \cdot m_B \quad \ldots \text{for abdomen}
\]

\[
\Omega_C = \sqrt{\frac{k_C}{m_C}} \Rightarrow k_C = \Omega_C^2 \cdot m_C \quad \ldots \text{for soles}
\]

The described state may be schematically represented by fig. 5.

![Fig. 3. Laparoseismographic recording of vibrations GUTO.](image)

**Fig. 3.** Laparoseismographic recording of vibrations GUTO.

![Fig. 4. Impact fall on the heels – reaction \(F_2\)[N].](image)

**Fig. 4.** Impact fall on the heels – reaction \(F_2\) [N].

Frequency \(\Omega\), damping \(\xi\) and stiffness \(k\) of the system are derived from the relations for harmonically damped motion. Basic equation of this motion is:

\[
y(x)=v_0 \cdot e^{-\xi x} \cdot \sin \frac{x}{T}
\]

Parameters of the harmonic damped motion are:

- \(T\) ... time of one period (we read from recording)
- \(v_0, v_1\) ... following amplitudes of motion (we read from recording)

Frequency \(\Omega\) resp. coefficient of damping \(\xi\) derived from relations:

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\]

The described state may be schematically represented by fig. 5.

![Fig. 5. Stiffness of system abdomen and rest of body.](image)

**Fig. 5.** Stiffness of system abdomen and rest of body.

\(k_b\) ... stiffness of abdomen

\(k_c\) ... stiffness of system

\(m_b\) ... mass of abdomen

\(m_{zb}\) ... mass of rest of system

\(m_c\) ... mass of system

Frequencies, dampings and stiffnesses are in the table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>STRIP</th>
<th>No. 54007</th>
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<tbody>
<tr>
<td>(\Omega_B) [s(^{-1})]</td>
<td>5,417</td>
<td>(\xi_B) [s(^{-1})]</td>
</tr>
<tr>
<td>(k_B) [Nm(^{-1})]</td>
<td>146,7</td>
<td>(m_{zb})</td>
</tr>
</tbody>
</table>

| Parameters     | PLAT FORM |   |
|----------------|------------|
| \(\Omega_C\) [s\(^{-1}\)] | 6,289   |
| \(\xi_C\) [s\(^{-1}\)]   | 15,073   |
| \(k_C\) [Nm\(^{-1}\)]   | 2729,3   |

Damping was set at values:

\(b_b = 123,1\) Nsm\(^{-1}\) – tangent damping,

\(b_c = 314502\) Nsm\(^{-1}\) – transversal damping

By comparison of signals on the desk in peace state and during fall we get overloading that starts in the area of soles at the moment of the fall from the known height (about 80 mm).

\[
\frac{s_{\text{drop}}}{s_{\text{still}}} = \frac{1374}{616} = 2,23
\]

In the sphere of dynamographic data – KISTLER platform – parameters for basic impact wakening of the whole gravid body system during interaction with the underlay, simulating impact similar to sliding on the stairs.
Basic values of maximum deceleration of the simulated fall down to the heels from a stair step reach the level of 2.2G (1511 N) and impulse of 40 Ns with the time period of 60 ms.

**Strength of Myometrium**

The prerequisite for a detailed simulation of the impact load upon myometrium is awareness of its basic characteristics. 12 myometrium samples were used in the tear-test to obtain the strength characteristics, see table 2 above.

**The tear-test outcomes imply that in the samples tested:**
- the ultimate strength ranges between 0.1–1.1 MPa,
- cross-section of samples exhibits strength 4 times higher than in longitudinal section,
- the average value of the ultimate strength in the samples tested is 0.333 MPa,

**Discussion**

Vibration of the gravid abdomen results from the gravid woman’s movements (physical activities), shocks or other mechanical interactions with the environment, in all possible directions. In the upright position, the abdomen, cambering forward, is in constant mechanical contact with other objects, which causes increased risk of mechanical exertion, which may affect the pregnancy. Unfortunately, when testing and analysing the impact, the analysis cannot be applied to animals, as the erect position associated with a specific position of the uterus can be found only in humans [10]. The experiment should represent a common type of impact corresponding to a probability of everyday risk for this frequency. The resonant zone is considered one of the high-risk zones for the foetus.

The resonant zone is described by resonant frequency of the uterus system and its attachment to os sacrum. Rigidity $k$ – rigidity of all absorptive attachments of the uterus, $k_b$ – damping effect of topically relevant organs on the uterus’ movement particularly represented by the whole frontal abdominal wall in the vertical direction.

The frequency of the gravid uterus and topically relevant organs in the frontal plane of vibration is approx. 8 Hz. It implies high sensitivity to resonance especially for this frequency. The resonant zone is considered one of the high-risk zones for the foetus.

Mechanical vibration of low frequency, related to associated organs, may result in separation of them, which may cause e.g. abruptio placentae. It may often occur despite the fact there was no direct impact on the gravid uterus. The vibration may lead to separation of the amnion in the lower segment and cause amniotic fluid outflow. It may also lead to premature contrac-
tions, which usually follow the Hamilton’s touch. The vibration may induce entero-uterine reflexes, leading to uterine contractions. The system’s vibration may also cause transmission of foetal blood cells into the blood circulation of the gravid woman. Critical exciting frequency may occur when travelling by means of transportation etc.

The vibration frequency of GUTO varies in the inter- and intra-individual aspect. It has to be taken into account that a simple mechanical interpretation may lead to inappropriate simplification, as the functional unit observed in the response (GUTO) is composed of various tissue types. In inter-individual characteristics differences in the composition of topical tissues and organs are relevant, as well as the actual state of muscle tonus and active changes in muscle contractions. Some of the characteristic points, as it is present in intra-individual assessments, may be changed by voluntary and involuntary mechanisms during the course of impact load. It concerns one of the very important characteristics of the biological system – adaptation. The adaptation also involves improvements of mechanical characteristics of tissues (e.g. muscle tissues – increase in the resulting muscle strength, ligament bone and other tissue characteristics, etc.) as a response to the load. It also involves various types of reflexes – their changes, anticipation of expected interactive situations, changes in reological characteristics of tissues, biochemical and bioelectrical changes, etc. In other word anisotropic structures of biological materials do return back to the initial state after they have been unloaded, which means there is no unique reference system describing stress-deformation relation.

Frequency reflects also other quantities – stiffness $k$ and the weight of the uterus with the foetus $m$. This implies that with changes in the weight of the uterus and its mechanical characteristics, e.g. in multiple pregnancy, the frequency of the whole system will change.

**Conclusion**

As seen from the biomechanical viewpoint, this is a pilot study, introducing new approaches (biomedical engineering) to obstetrics, which have been neglected. This approach objectivizes, makes precise and enhances theoretical knowledge necessary for preventive care in pregnancy. The practical outcomes can be noted in obstetric implications, work and leisure activities and in transportation traumatology.

The parameters obtained contribute to the modelling of load in pregnancy, which will be further described in our following studies.

**Acknowledgement**

This project have been supported by GAUK no 318/1997/C.