THE ARCHIVE OF MECHANICAL ENGINEERING

Vol. XLVII 2000 Number 1

Key words: *hydraulic hammer, impact energy*

KRZYSZTOF KRAUZE[*)]

EXPERIMENTAL DETERMINATION OF IMPACT ENERGY OF HYDRAULIC HAMMERS

The necessity of empirical determination of impact energy of hydraulic hammers prompted the Author to analyse the methods that had previously been used to determine this quantity. Based on the results of the analysis, the Author developed a new method of measurement of impact energy by means of force converter with an embedded elastic element. Taking into consideration the structural scheme and the principle of measurement, one derived analytical relationship that make it possible to calibrate the measuring system in energy units. A practical example of application of the developed system was in measurements of impact energy of hydraulic hammers used in Polish copper mining industry.

1. Introduction

In industrial applications, many kinds of tools and machinery deliver energy in the form of an impulse. One can mention impact hammers that transfer kinetic energy from the ram through the tool (striker) to the rock. The result of it is destruction of cohesion of the rock, i.e. mining.

In the process of rock mining by impact hammers, one needs such devices whose energy and stroke frequency enables the worker to perform the task according to user's requirements. For this reason, producers specify basic parameters of impact hammer, essential for its performance, such as:

- impact energy,
- stroke frequency,
- supply ratings adequate for the required impact energy and stroke frequency.

Because most of impact hammers are powered pneumatically or hydraulically, supply parameters mean output flow and pressure of the supply

*) *Academy of Mining and Metallurgy Kraków, Department of Mining, Dressing and Transport Machines; Al. Mickiewicza 30, 30-059 Kraków, Poland; E-mail: krauze@uci.agh.edu.pl*

units (hydraulic units, compressors) that deliver the working medium to the hammer. The user is interested in applying such a hammer that gives the required values of impact energy and frequency with minimum supply ratings.

One must mention that, up to now, the producers of hydraulic hammers have been using different methods to determine impact energy. The result is that the energy values, quoted by different producers, are incomparable. Consequently, the user can make a proper choice while selecting a hydraulic hammer only by testing the device. Because of these ambiguities, the Mounted Breaker Manufacturers Bureau (MBMB), and the Construction Industry Manufacturers Society (CIMA) in the U.S.A. have declared that there is a need for developing a consistent and repeatable method for measurement of impact energy [1].

The method of impact energy measurement, developed by CIMA/MBMB, is based on measurement of stress wave generated by the ram striking into the striker. As the wave travels along the tool, its magnitude is measured by a set of strain gauges attached to the striker.

The method is accepted by most of the leading producers of impact hammers. However, it allows only for direct measurement of impact energy, and indirect measurement of frequency. For this reason, it can be used only for measurement of impact energy and frequency, and for comparative investigations on different types of impact hammers. It should also be mentioned that, in order to measure the stress wave, strain gauges must be mounted on the striker anew in each measurement. It creates a significant inconvenience, because gluing of the strain gauges must be done meticulously, and the whole striker must undergo a new calibration process. Another disadvantage of the above method, noticed by the Author in practical applications, is low durability of the strain gauge system. It deteriorates very quickly in high acceleration conditions due to the transmission of energy from the ram to the striker (elastic collision). In many cases, a break of electric connection in the strain gauge circuitry may occur already after a few strikes, and the whole process of sensor mounting must be repeated.

The above mentioned inconveniences of the method, as well as shortcomings of other methods known from literature [2], gave the Author an inducement to look for such a solution that would make the measurement of impact energy and frequency of impact hammers more precise, reliable and less costly.

An additional condition, necessary for determining efficiency of the examined device, is the requirement of measuring its supply parameters (pressure, flow intensity) by means of a separate set of transducers [3], [4], [5]. Evaluation of efficiency of impact hammers makes it possible to compare the hammers with one another, irrespective of differences between supply parameters used by different producers.

It can be assumed that energetic efficiency of hydraulic hammer is given by general relationship [2]

$$\eta_c = \eta_h \eta_m \tag{1}$$

where:

η_h – efficiency of the internal hydraulic system of the hammer (hydraulic efficiency),

$$\eta_h = \frac{E_j n}{p_z Q_z} \tag{2}$$

η_m – efficiency of the system ram-striker-rock (mechanical efficiency),

$$\eta_m = \frac{L_u}{E_j} \tag{3}$$

E_j – impact energy,

n – stroke frequency,

p_z – supply pressure,

Q_z – flow intensity on supply side,

L_u – usable impact energy.

In the case of examination of a hammer in a measuring position, the only interesting quantity is hydraulic efficiency η_h given by formula

$$\eta_h = k_p k_\Theta \tag{4}$$

where:

k_p – proportionality coefficient of impact energy and supply pressure, kJ/MPa

$$E_j \approx k_p p_z , \tag{5}$$

k_Θ – proportionality coefficient of frequency and supply flow intensity, $1/\mathrm{dm}^3$

$$n \approx k_\Theta Q_z \tag{6}$$

The efficiency η_h can be determined from equation (2) or (4). However, for measurement purposes, it is more convenient to use the latter.

2. Measurement system

The conclusion that can be drawn from descriptions of possibilities of measurement of impact hammer energy is that the measuring system must contain:

- Energy transducer, E_j,
- Transducer of supply pressure p_z,
- Transducer of supply flow intensity Q_z.

Once these components are applied, the considered system can meet the requirements concerning the ability to measure energy and frequency of stroke, as well as efficiency of the impact hammer. Bearing in mind the objections about the commonly used methods of energy evaluation, the Author decided to construct energy transducer designated for this purpose. As far as other quantities are concerned, adequate transducers are easily available and can be applied for measurement.

The measurement of the above-mentioned quantities also involves data processing and recording. In the measurements, one decided to apply a computer with an appropriate hardware (measurement boad) and software for signal recording and analysis.

2.1. Energy transducer

For measurement of impact energy in hydraulic hammers, one chose an indirect method consisting in stress measurement by a force transducer placed under the striker. The application of a separate transducer makes it possible to avoid the above mentioned inconveniences and disadvantages existing in other systems.

The considered transducer consists of two parts (Fig. 1). The first part, shaped as a stepped roller *1* with strain gauges fixed to it, is a conventional transducer for measurement of stresses (forces) resulting from external load. The second part, set on the measuring roller *1*, is the cylinder *2* with an elastic element *3* placed inside it. A cap *4* that supports the striker covers the top of the cylinder *2*. The structure of transducer and the number of its parts were optimized with respect to the magnitude and frequency characteristics of the measured stresses. Transducer reliability and durability was also taken into account. The choice of the specific structure of transducer and strain gauge set-up (stress measurement) implies that an appropriate calibration method should be developed.

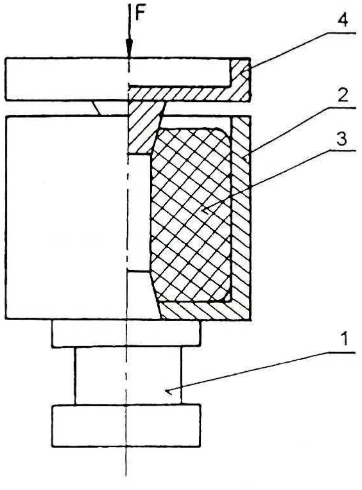

Fig. 1 Structural diagram of energy transducer

2.2. Calibration of transducer in energy units

In order to calibrate the transducer, one applied the principle of equivalence of kinetic (measured) energy and potential (reference) energy. Calibration is carried out in a measuring position. Its operating principle gives the possible to lower the reference mass m_w that drops down in free fall from the height h_w onto the transducer of mass m_c (Fig. 2).

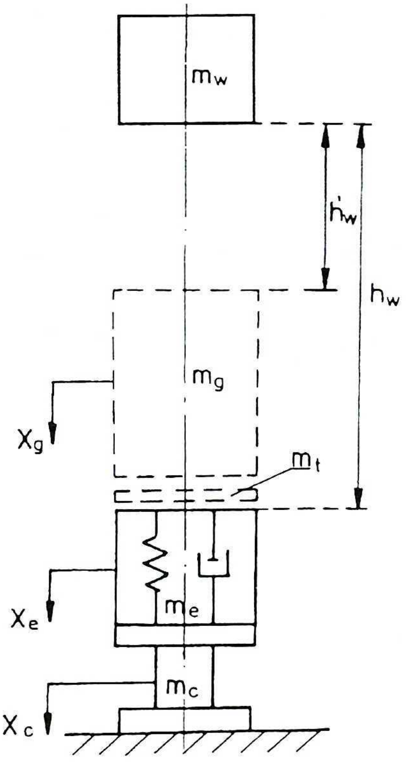

Fig. 2 Schematic diagram of the force transducer calibration system

The energy transmitted into the transducer

$$E_w = m_w g h_w \tag{7}$$

evokes a wave of stress σ_{cw} that is measured by a set of strain gauges. The relationship between the reference energy E_w, the measured energy E_m, the reference stresses, and the measured stresses can be written as [1], [2], [5], [6]

$$E_m = E_w \left(\frac{\sigma_m}{\sigma_w} \right)^2 \tag{8}$$

or, for equal surfaces

$$E_m = E_w \left(\frac{P_m}{P_w} \right)^2 \tag{9}$$

where: P_m – measured force,

P_w – reference force.

It follows on equation (8) or (9) that for each specific value of reference energy E_w (h_w=const.) one must accurately determine (by applying the least square method) the value of stress or force. In the next step, the value of kinetic energy can be determined analytically, as the functions of σ_m and P_m are known from measurements. Of course, this problem can only be solved if the force transducer characteristic is known, and that can also be determined by calibration.

$$P = kA \tag{10}$$

where: P – force, N,

k – proportionality coefficient, N/mV,

A – output voltage of strain gauge set, mV.

In the examination of hydraulic hammer, the energy of hammer stroke (energy of the ram) is transmitted to the transducer through the striker. The presence of an additional mass m_g (mass of the striker) requires that one should take this mass into account in calibration factors. The actual energy transmitted through the striker to the transducer equals (according to the theory of elastic collision)

$$E_g = \frac{4 m_g m_w}{\left(m_w + m_g\right)^2} E_w \tag{11}$$

It follows from equation (11) that the energies E_g and E_w can differ only if m_w (reference mass) and m_g (striker mass) are different.

While determining hammer energy, one must also consider the fact that the force exerted on the transducer consists of that related to the impact of hammer mass and the press-down force. The value of stress created by the press-down force defines energy E_n responsible for producing such a stress. Therefore, the measured value of hammer impact energy E_m must be decreased by this factor

$$E_m' = E_m - E_n \tag{12}$$

$$E_m' = \frac{4 m_g m_w}{\left(m_w + m_g\right)^2} \left[\left(\frac{P_m}{P_w} \right)^2 - \left(\frac{P_n}{P_w} \right)^2 \right] E_w \tag{13}$$

or

$$E_m' = \frac{4 m_g m_w}{\left(m_w + m_g\right)^2} \left[\left(k_m A_m\right)^2 - \left(k_n A_n\right)^2 \right] \frac{E_w}{\left(k_w A_w\right)^2} \tag{14}$$

where: A_w, A_m, A_n – strain gauge voltages (in mV) due to forces P_w, P_m, P_n, respectively,

k_w, k_m, k_n – calibration constants of forces P_w, P_m, P_n in the case of nonlinear transducers characteristic; otherwise $k_w = k_m = k_n = k$.

$$E_m' = \frac{4m_g m_w}{(m_w + m_g)^2 A_w^2}\left(A_m^2 - A_n^2\right)E_w \tag{15}$$

The relations (14) and (15) were derived for the case of equality of reference mass m_w and striker mass m_b. In the other case, when $m_w \neq m_b$, there is

$$E_m' = \frac{4m_g m_w^2}{m_b (m_w + m_g)^2 A_w^2}\left(A_m^2 - A_n^2\right)E_w \tag{16}$$

Once the transducer is calibrated in energy units, it can also be applied in the systems where calibration parameters are different from those of the original hammer. To take the differences into account, one can use the above formulas and calculate actual values of the considered parameters.

2.3. Final remarks

The described energy transducer and the remaining elements of the measuring system were made in the plants of the ZG "Rudna" copper mine at Polkowice, Poland. The method of calibration was also developed there, and applied in a diagnostic stand for measuring hydraulic hammers.

3. Example of measurement of impact energy of hydraulic hammer

As it was mentioned before, the energy transducer was used in a measuring stand in the "Rudna" copper mine [3], [4], [5]. This facility makes it possible to measure, visualize and register the following quantities (external parameters of the hammer);

1. Impact energy CF – strain gauge (KMG AGH),
2. Stroke frequency CF – strain gauge (KMG AGH),
3. Hammer supply pressure PC1 – piezoelectric transducer (Danfoss),
4. Hammer run-off pressure PC2 – piezoelectric transducer (Danfoss),
5. Supply flow – turbine transducer (IL),
6. Run-off flow – turbine transducer (IL),
7. Temperature of oil on supply side CT2 – resistance thermometer (KFAP).

To visualize and analyze the data on-line, the measuring system was controlled by a PC-486 DX4/100 computer with installed measurement board PCL-812PG. Transducer outputs were connected to 12 bit A/D converters (sampling frequency 25kHz) through amplifiers in the board type PCLD-5B16;

additional amplifier type PCLD-5B38 was used for the force (energy) transducer, and one type PCLD-5B34 for the resistive thermometer. Special software, based on the DASYLab software package, was developed for data recording, analyzing, and creating reports on the measurement results. The schematic diagram of the stand for measurement of external parameters of hydraulic hammers is shown in Fig. 3. Fig. 4 presents a photograph of the stand with a hammer mounted in it.

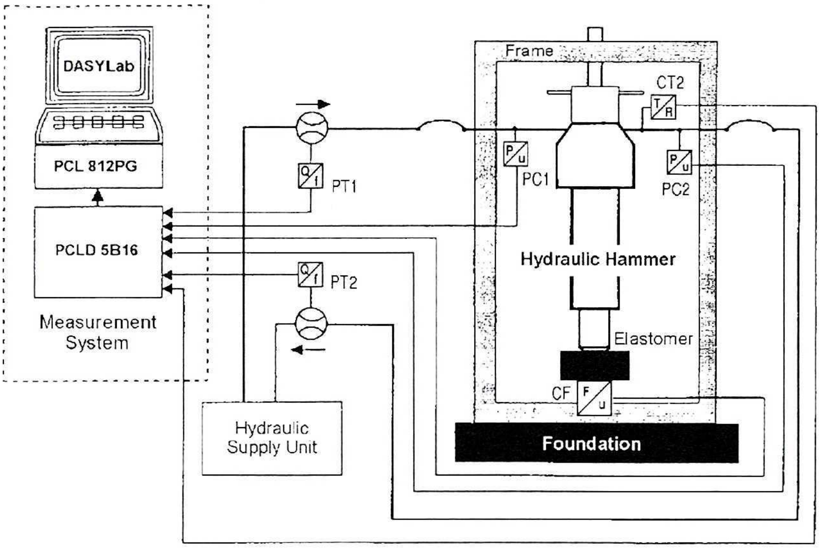

Fig. 3 Schematic diagram of the stand for measurement of hammer external parameters

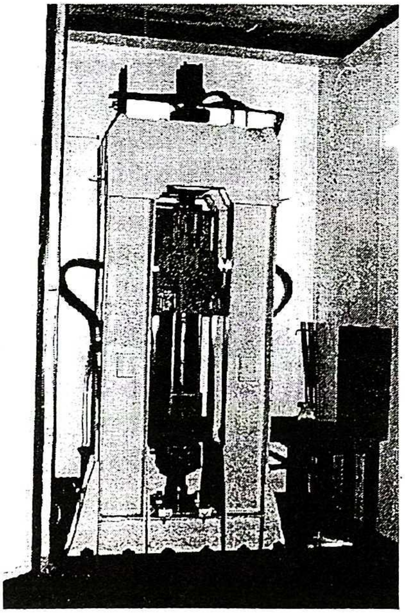

Fig. 4 Photograph of the stand with mounted hammer

The cycle of tests performed in examination of a hammer can be divided into three stages:

- Stabilizing hammer working temperature,
- Measuring hydraulic and energetic parameters of the hammer (Figrs 5 and 6),
- Analyzing measurement results and creating report (Fig. 7).

The obtained results of measurement are then used for assessment of technical condition of the examined hammer.

As one can notice, the measurement procedure does not include calibration of the energy transducer. It is due to the fact that transducer's durability proved very high. However, it is recommended that the transducer should be periodically (every 60 days) checked and calibrated according to the procedure described in the previous sections.

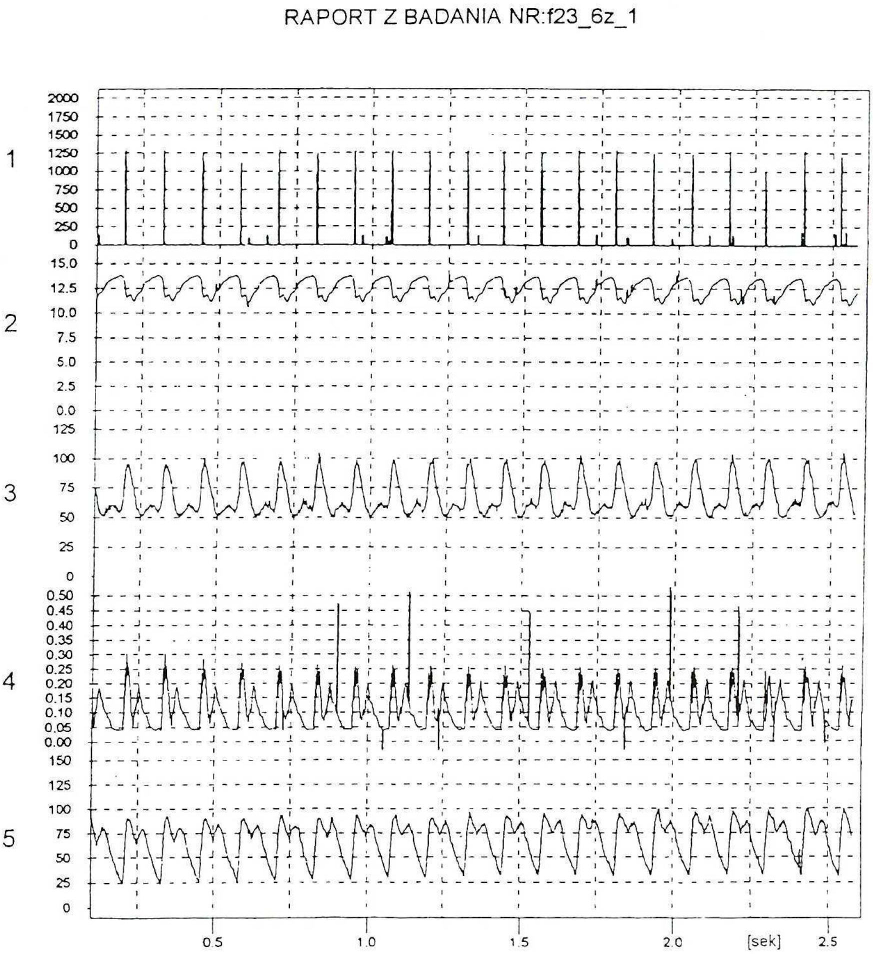

Fig. 5 Example waveforms of quantities measured in examination of hydraulic hammer
1 – energy; Nm, *2* – supply pressure, MPa; *3* – supply flow, dm^3/min;
4 – run-off pressure, MPa; *5* – run-off flow, dm^3/min

TEST RESULTS; TEST No. f23_6z_1

Energy Nm	Pz. Max MPa	Pz.min. MPa	Qz.max dm^3/min	Qz.min dm^3/min	Ps.max MPa	Ps.min MPa	Qs. max dm^3/min	Qs.min dm^3/min	Frequency Stroke/sec	Hammer Temp. [°C]	K_p kJ/MPa	K_q $1/dm^3$	Efficiency
433.298	13.831	10.802	101.250	0.000	0.262	0.037	200.000	23.750	15.321	44.156	0.031	9.079	0.284
1289.654	13.857	11.205	95.000	51.250	0.302	0.040	91.250	23.750	8.049	44.391	0.093	5.084	0.473
1245.107	13.818	11.160	101.250	50.000	0.303	0.038	92.500	23.750	8.233	44.090	0.090	4.879	0.440
1113.460	13.798	10.560	97.500	50.000	0.271	0.041	90.000	26.260	8.319	43.947	0.081	5.120	0.413
1286.733	13.787	11.101	97.500	50.000	0.264	0.034	93.750	27.500	8.354	43.836	0.093	5.141	0.480
1269.890	13.782	11.098	105.000	50.000	0.473	0.038	92.500	27.500	8.082	43.461	0.092	4.618	0.426
1278.586	13.796	11.112	98.750	50.000	0.263	-0.055	93.750	30.000	8.407	43.032	0.093	5.108	0.473
1272.781	13.871	11.093	100.000	50.000	0.511	-0.072	90.000	30.000	8.407	42.829	0.092	5.044	0.463
1275.113	13.764	11.086	100.000	50.000	0.262	0.036	96250	31.250	8.407	42.499	0.093	5.044	0.467
1238.239	13.713	11.040	98.750	50.000	0.448	0.038	96.250	31.250	8.552	42.168	0.090	5.196	0.469
1277.404	13.694	11.020	103.750	50.000	0.257	0.036	93.750	32.500	8.461	41.983	0.093	4.893	0.456
1287.891	13.677	10.990	98.750	50.000	0.248	-0.060	95.000	31.250	8.233	41.856	0.094	5.002	0.471
1234.239	13.922	10.940	100.000	51.250	0.532	0.034	100.000	32.500	8.182	41.437	0.089	4.909	0.435
1278.600	13.603	10.911	105.000	51.250	0.467	0.036	97.500	32.500	8.216	41.557	0.094	4.695	0.441
1277.418	13.574	10.905	100.000	50.000	0.246	-0.007	98.750	32.500	8.552	41.048	0.094	5.131	0.483
1205.838	13.532	10.857	105.000	50.000	0.263	-0.010	100.000	31.250	8.233	41.210	0.089	4.705	0.419

Fig. 6 Juxtaposition of external parameter values of the examined hydraulic hammer

DIAGNOSTICS

Hammer No.	Card No.	Test Date	Test Description
f23_z	0	98-06-25	f23_6z_1

Table of Measurements

No.	Energy Nm	Pz. Max MPa	Pz.min. MPa	Qz.max dm^3/min	Qz.min dm^3/min	Ps.max MPa	Ps.min MPa	Qs. max dm^3/min	Qs.min dm^3/min	Frequency Stroke/s	Hammer Temp. [°C]	K_p kJ/MPa	K_q 1/dm^3	Efficiency
1	1245	13.82	11.16	101.3	50.0	0.30	0.04	92.5	23.8	8.23	44.1	0.090	4.879	0.440
2	1287	13.79	11.10	97.5	50.0	0.26	0.03	93.8	27.5	8.35	43.8	0.093	5.141	0.480
3	1279	13.80	11.11	98.8	50.0	0.26	-0.06	93.8	30.0	8.41	43.0	0.093	5.108	0.473
4	1273	13.87	11.09	100.0	50.0	0.51	-0.07	90.0	30.0	8.41	42.8	0.092	5.044	0.463
5	1275	13.76	11.09	100.0	50.0	0.26	0.04	96.3	31.3	8.41	42.5	0.093	5.044	0.467
6	1238	13.71	11.04	98.8	50.0	0.45	0.04	96.3	31.3	8.55	42.2	0.090	5.196	0.469
7	1277	13.69	11.02	103.8	50.0	0.26	0.04	93.8	32.5	8.46	42.0	0.093	4.893	0.456
8	1288	13.68	10.99	98.8	50.0	0.25	-0.06	95.0	31.3	8.23	41.9	0.094	5.002	0.471
9	1234	13.92	10.94	100.0	51.3	0.53	0.03	100.0	32.5	8.18	41.4	0.089	4.909	0.435
10	1277	13.57	10.90	100.0	50.0	0.25	-0.01	98.8	32.5	8.55	41.0	0.094	5.131	0.483

Calculations

	Energy Nm	Pz. Max MPa	Pz.min. MPa	Qz.max dm^3/min	Qz.min dm^3/min	Ps.max MPa	Ps.min MPa	Qs. max dm^3/min	Qs.min dm^3/min	Frequency Stroke/s	Hammer Temp. [°C]	K_p kJ/MPa	K_q 1/dm^3	Efficiency
X	1267	13.76	11.04	99.9	50.1	0.33	0.00	95.0	30.3	8.38	42.5	0.092	5.035	0.464
DX	19.23	0.0968	0.0776	1.631	0.390	0.1095	0.0451	2.800	2.603	0.1236	0.935	0.00170	0.10646	0.01504

Remarks

Toz = 52°, Tm = 47°, Tom = 44°, Valve No. 1

Fig. 7 Juxtaposition of results of statistical processing of measurement data. The parameters allow for assessment of technical condition of the examined hydraulic hammer

4. Conclusion

Force transducer with an embedded elastic element, working within the measuring system of the diagnostic stand for examination of hydraulic hammers, is utilized for measurement of impact energy of the hammer. The structure of the transducer and properties of the set of strain gauges make it possible to achieve high durability of the system, and high precision of measurements. This conclusion can be well confirmed by the results of implementation of the system in the ZG "Ruda" copper mine. The energy transducer can also be adapted, without the necessity of calibrating it anew, to measurement of other types of hammers. One should only use the formulas from previous sections to re-calculate appropriate parameters.

Manuscript received by Editorial Board, April 23, 1999;
final version, January 31, 2000.

REFERENCES

[1] Rammer R.: New Method of Measuring Hydraulic Hammer Impact Energy. The only Magazine for the Breaking Business, No. 1/97.

[2] Korzeń Z., et al.: Analiza tendencji w budowie młotów hydraulicznych dla potrzeb górnictwa. Prace Naukowe Politechniki Wrocławskiej, 42 seria Konferencje 7, Wrocław, 1984.

[3] Krauze K., Pluta J., Podsiadło A., Micek P.: Badanie ciężkich młotów hydraulicznych. VI Ogólnopolskie Sympozjum pt. „Badanie, konstrukcja, wytwarzanie układów hydraulicznych, Cylinder'96", Zakopane 1996.

[4] Krauze K., Pluta J., Maziarz M., Tylek R., Laska Z.: Stanowisko diagnostyczne młotów hydraulicznych. X Konferencja Naukowa pt. „Problemy rozwoju maszyn roboczych", Zeszyt Nr 2, Zakopane 1997.

[5] Krauze K., Micek P., Krawczyk S.: Metodyka badań młotów hydraulicznych na stanowisku laboratoryjnym. III Konferencja Naukowa pt. „Metody doświadczalne w budowie i eksploatacji maszyn", Wrocław – Szklarska Poręba 1997.

[6] Bęben A.: Dynamika maszyn górniczych. cz. III. Skrypt Uczelniany nr 1131, Wydawnictwo AGH, Kraków 1988.

Eksperymentalne wyznaczanie energii udarów młota hydraulicznego

Streszczenie

Konieczność empirycznego określenia energii udaru młotów hydraulicznych była przyczyną analizy dotychczas stosowanych metod pozwalających wyznaczyć poszukiwaną wielkość. W konsekwencji przeprowadzonej analizy opracowano nowy sposób pomiaru energii udaru przy wykorzystaniu przetwornika siły z wbudowanym elementem sprężystym. W oparciu o konstrukcję przetwornika siły i metodę pomiaru opracowano zależności analityczne umożliwiające wzorcowanie układu pomiarowego w jednostkach energii. Praktyczne wykorzystanie opracowanego układu pomiarowego opisano na przykładzie pomiaru energii młotów hydraulicznych stosowanych w polskich kopalniach miedzi.