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# DIGITAL MEASUREMENT USING SHIFT KEYED SYMBOLS

***I.A. Henderson [1], L. Jackowska-Strumillo [2] and J. McGhee [1]***
[1] Industrial Control Centre, University of Strathclyde, Glasgow, Scotland
[2] Computer Engineering Department, Technical University of Lodz, Poland

*Abstract: The transfer of information theory from data communications to digital measurement in the form of the coding theorems, descriptive languages and data patterns, has provided new digital signals. In this paper, shift keyed symbols are used to design Symbolic Addition (SA), Phase Shift Keyed (PSK) and Frequency Shift Keyed (FSK) signals. These allow different aspects of a frequency response to be investigated with one signal and one experiment. Symmetrical versions of these signals allow a set of Multifrequency Identification Patterns (MIPs) which can capture and monitor different multifrequency characteristics. SA signals are useful for obtaining information at the phase crossover allowing the determination of controller settings in auto-tuning or adaptive control. PSK signals 'zoom in' and give accurate details of, say, a peak in the closed loop frequency response while FSK signals highlight two or more portions of the frequency response. This allows the system parameters to be continuously monitored and analysed. These shift keyed signals are applied to different systems where an MIP or frequency information may be obtained.*

*Keywords: Digital Measurement, multifrequency signals, shift keyed modulation*

## 1 INTRODUCTION

Two well known digital signals are the squarewave and Pseudo Random Binary Sequence (PRBS) [1] signals. As the squarewave has 81 % of its energy in one frequency (fundamental) and the PRBS signal spreads its energy widely over many frequencies, they are at the extremes of what is required from a multifrequency measurement signal. There is an infinite possibility in terms of the power distribution and the number of frequency estimates between the extremes which are given by these two important signals. A new design philosophy [2] is required to fill the gap in this knowledge. Also, there is a need for a wider range of digital signals in frequency response measurement.

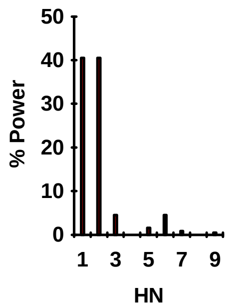
Coding theory is concerned with the optimal manner in which information is contained in the symbols and the time domain patterns [2,3] they represent. Thus, system identification is closely allied not only to measurement but also to pattern recognition. The two data communication coding theorems were rewritten in terms of symbols capturing information and renamed the identification source and channel coding theorems. It was immediately realised that the identification source coding theorem implied minimum alphabetical representation (Minimum DAC levels) and minimum total number of symbols giving minimum complexity for the description of the data measurement signal to capture specific information from the measurement channel. Measurement Codes (MCs), where complementary alphabetical symbols correspond exactly to DAC output levels, are used to describe and design suitable test signals [2,3]. The identification coding theorems and symbolic operations may be applied in the design of a variety of precise digital signals. The main symbolic operations are symbolic coding, symbolic addition [2], phase shift keying [2,3], and frequency shift keying [3]. This paper designs and applies novel digital signals using shift keyed symbols.

## 2 SYMBOLIC ADDITION

Symbolic addition [2] is an important basic operation in the signal engineering of digital signals. It relies on the addition of signals in the time domain. When the two signals, $x_1(t)$ and $x_2(t)$, with the same total number of alphabetic symbols and Fourier Transforms, $X_1(j\omega)$ and $X_2(j\omega)$, are added in the time domain, then the Fourier Transform of this time domain sum is the complex sum of their spectra. To ensure the identification channel set point is unaltered, digital signals must be designed with zero mean output voltage. This means that the measurement codes have the c symbol as 0 V and the same number of complementary alphabetical symbols i.e. $N_a$=$N_b$, $N_d$=$N_e$, etc. In forming the test signal from the measurement code, complementary DAC voltage levels will be obtained.

The symbolic added SquareWave 1+2, or SqW 1+2, signal in figure 1 is formed by adding two squarewaves. Only the fundamental frequency and the second harmonic of each of the added squarewaves need to be considered in forming this Multifrequency Ternary Sequence (MTS) signal. This is sufficient as the squarewaves are noninteracting at these dominant harmonics. The Parseval power in the signal corresponds to the power which would be dissipated in a resistor of 1 Ω in accordance with Parseval's Theorem. Within the normalised limits, all Multifrequency Binary Sequence (MBS) signals have the maximum Parseval power of 1 W.

MC:- **O,** ac
Parseval power = 0.5 W
Selected power = 81.06 %
**k  $a_k$  $b_k$  $P_k$ %**
10.00000.636640.53
20.00000.636640.53



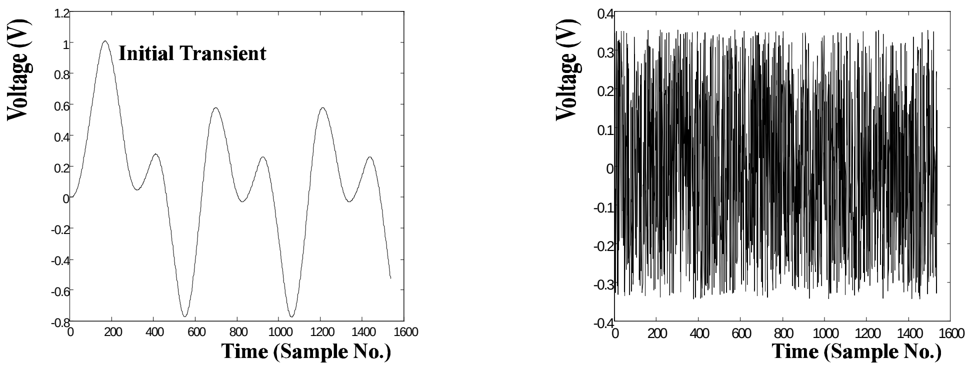

a a b b **1** (1st Harmonic)
a b a b **2** (2nd Harmonic)
(2a)(0) (0)(2b) **1+2**
or a c c b

Using odd, **O,** symmetry this becomes

**O**, ac

**Figure 1.** Unweighted symbolic addition to form the SqW 1+2 signal

The output signal for three periods of a SqW 1+2 digital signal is given in figure 2(a). Noise with a variance of ≤ 0.7, which was added to the simulated process output, left the frequency information unaltered. Figure 2(b) shows the same output as in figure 2(a) but with the addition of the noise. Shift keyed digital signals allow an excellent system identification even under very noisy practical conditions.



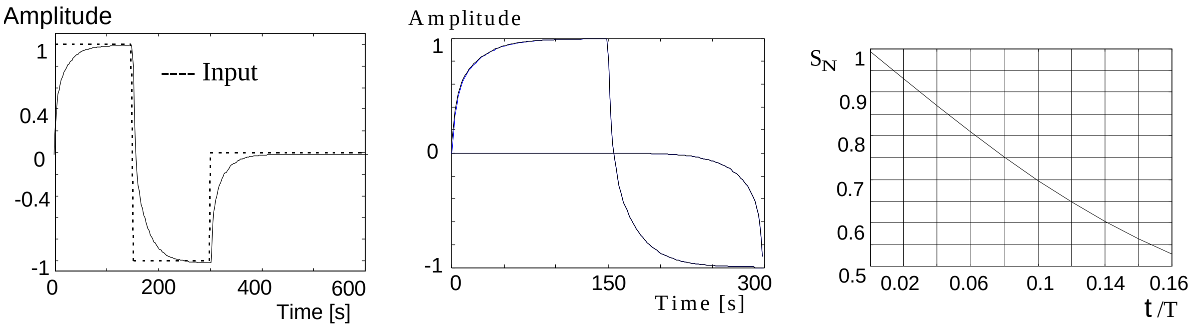

(a) (b)

**Figure 2.** Output of process $1/(s+1)^3$ with SqW 1+2 digital signal (a) without noise (b) with noise of variance 0.7

Figure 3(a) shows the time waveform for the input signal and the corresponding output of a simulated RTD sensor. The corresponding Multifrequency Identification Pattern (MIP), is given in figure 3(b). The enclosed area of the output MIP is used for sensor condition monitoring [4-6]. Provided the signal period, T, is much greater than the dominant time constant, $\tau$, there is a linear relationship between the normalised enclosed area, $S_N$, and $\tau/T$ as shown in Figure 3(c). Figure 4(a) shows the Nichols plot obtained using the SqW 1+2 signal which is used to measure the phase crossover for the auto-tuning or adaptive control of an industrial electric resistance furnace [7]. Figure 4(b) shows the determination of the angular frequency at the crossover which is used to tune the controller.

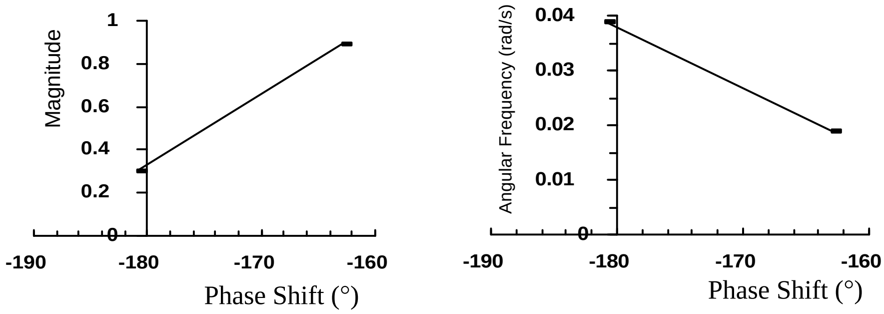
## 3 PHASE SHIFT KEYING

Modulation by phase shift keying [2,3] may be applied to a squarewave carrier where a compact modulated signal is produced by a carrier which is Phase Shift Keyed (PSK) by a compact modulating




(a) (b) (c)

**Figure 3.** Monitoring RTD sensor with **abcc** test signal with no switch-on transient (a) input and output time domain responses (b) MIP for output signal (c) normalised MIP area versus τ/T




(a) (b)

**Figure 4.** (a) Nichols plot for an industrial electric resistance furnace (b) graph of angular frequency against phase shift at phase crossover

signal. The spectral signature of a PSK sequence consists of upper and lower side bands about a central suppressed squarewave fundamental carrier frequency. If the suppressed carrier harmonic number is $h_c$ and the dominant harmonic numbers of the modulating signal are $h_n$, the upper harmonic number array and lower harmonic number array consist of $h_c + h_n$ and $h_c - h_n$ respectively. In this way, the test signal energy is concentrated into twice the original number of dominant harmonics which are available with the chosen modulating signal. This must favour modulation with a measurement code which has a low number of dominant harmonics. A bandwidth comparison may be made using the normalised bandwidth,

$$B_N = \pm \frac{100m}{NZ} \tag{1}$$

where Z is the range zoom factor, N is the number of modulating signal bits and m is its maximum dominant harmonic number. The number of PSK Symbols for $N_c$ carrier symbols,

$$N_{PSK} = NN_cZ \text{ where } Z=1,2,3,4,\text{etc} \tag{2}$$

With the aid of Z, a portion of a frequency response record may be detailed.

In digital PSK modulation, each modulating symbol is multiplied by Z and by the number of carrier bits, while the phase of the carrier is synchronised such that its phase is changed by 180 degrees every time the modulating code changes its logical level. There are alternate repetitions of the full cycle (ab) or the complement (ba) of the squarewave carrier when the phase of the squarewave is changed by 180 degrees due to the modulating signal changing its symbol or logic level.

Consider the S16B148 (S-Strathclyde; 16 Total number of symbols; B-Binary; 148-Number in catalogue [2]) which has the coding symbols **O**,abaaaaba or **O**,ab $a^4$ ba . PSK symbols are obtained by replacing a and b of the modulating symbols by (ab) and (ba) when Z=1. In terms of S this becomes **O**, S ↑S $S^4$ ↑S S , ab where S=ab and ↑S=ba. With any zoom factor the PSK-S16B148-Z symbols are **O**,$S^Z$ ↑$S^Z$ $S^{4Z}$ ↑$S^Z$ $S^Z$, ab. For a given modulating signal and zoom factor, this is the simplest method of obtaining the PSK symbols. Table 1 gives the full details for Z=1,2,3,4. There is an enormous reduction in the complexity [8]. Even as Z is increased with a large increase in the

**Table 1.** Strathclyde PSKMBS using the compact MBS S16B148

| PSKMBS | Harmonic Amplitude, $E_n$, a=1, b=0 | % Power | % P/Comp. |
|---|---|---|---|
| **S16B148-Z=1 N=32** | $E_7$ = 0.6362, $E_9$ = 0.7347, $E_{13}$ = -0.3809<br>$E_{15}$= 0.4882, $E_{17}$ = -0.4308, $E_{19}$ = 0.2606<br>$E_{23}$ = -0.2875, $E_{25}$ = -0.1781 | 84.79 | 10.60±8.30<br>$B_N$=±56.25 % |
| **S16B148-Z=2 N=64** | $E_{23}$ = 0.4988, $E_{25}$ = 0.6066, $E_{29}$ = -0.3491<br>$E_{31}$ = 0.4736, $E_{33}$ = -0.4449, $E_{35}$ = 0.2893<br>$E_{39}$ = -0.3889, $E_{41}$ = -0.2798 | 73.70 | 9.21±4.54<br>$B_N$=±28.13 % |
| **S16B148-Z=3 N=96** | $E_{39}$ = 0.4587, $E_{41}$ = 0.5676, $E_{45}$ = -0.3389<br>$E_{47}$ = 0.4688, $E_{49}$ = -0.4496, $E_{51}$ = 0.2990<br>$E_{55}$ = -0.4231. $E_{57}$ = -0.3138 | 71.81 | 8.98±3.64<br>$B_N$=±18.75 % |
| **S16B148-Z=4 N=128** | $E_{55}$ = 0.4394, $E_{57}$ = 0.5487, $E_{61}$ = -0.3338<br>$E_{63}$ = 0.4663, $E_{65}$ = -0.4520, $E_{67}$ = 0.3039<br>$E_{71}$ = -0.4405, $E_{73}$ = -0.3310 | 71.16 | 8.90±3.28<br>$B_N$=±14.06 % |

number of binary bits, there is very little change in the complexity. The output frequency information may be taken as plotted points in either a Nyquist, Inverse Nyquist, Bode or Nichols plot.

Figure 5 shows the identification of a very large but narrow closed loop peak in the frequency response which is due to an unbalanced load on the shaft of a position control system. The S16B148-Z=1 test signal gives the overall frequency response while the S16B148-Z=4 test signal is used to fill in the detail at the peak [9].

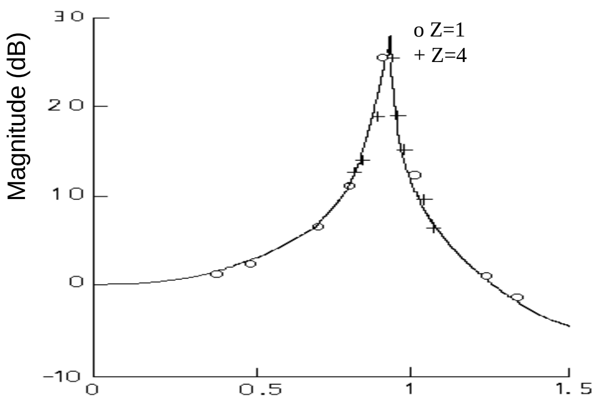



**Figure 5.** Identifying a closed loop peak of a position control system with an unbalanced load

## 4 FREQUENCY SHIFT KEYING

All digital signals have a switch-on transient which may be minimised. A normalised digital signal has a=1 V, b=-1 V while an MTS signal includes c=0 V symbols. In forming the test signal from the measurement code, complementary DAC voltage levels will be obtained.

One way of minimising the switch-on transient is to rotate the measurement code until the signal both starts and stops at 0 V. However, when a multisymbol code has c symbols, there is another possibility. The switch-on transient may be eliminated by allowing the final transient to decay to 0 V by the end of the first period. This is obtained by starting any on-line system identification with an asymmetrical version of the code which ends with the maximum number of c symbols.

The digital form of Frequency Shift Keyed (FSK) [3] modulation involves concatenating the time waveforms of two modulated carriers. The simplest design involves two different digital signals with the same total number of symbols, that is equal time intervals, before they are combined. Hence, an FSK signal with the measurement code $S_1S_2$ is formed from two measurement codes, $S_1$ and $S_2$, each with the same total number of symbols. As the time interval and signal processing window of each signal is doubled during the concatenation, the FSK dominant harmonic numbers are obtained by doubling the dominant harmonic numbers of each of the original signals. One half of the time waveform contains the frequency information of the dominant harmonics of $S_1$ multiplied by 2. while the other half contains the frequency information of the dominant harmonics of $S_2$ multiplied by 2.

In this paper, an MTS signal, the SqW 1+2, is used as the building block in the formation of FSK signals. The SqW 1+2 (MC **O**, ac) [1] energy is split equally between harmonic numbers 1 and 2. That is, the SqW has one dominant harmonic and SqW 1+2 has two dominant harmonics. In this design, the SqW 1+2 signal is used for both the lower and higher harmonics sets.

If the upper dominant harmonic set contains 16 and 32 or 8X2 and 16X2, a half code, $[ac^2b]^8$ is required where an exponent indicates repeated symbols or sets of symbols. The lower set, with the same number of symbols and dominant harmonics 2 and 4 or 1X2 and 2X2, has the half code $b^8c^{16}a^8$. The full FSK code is then

$$S_{FSK\text{-}MTS} = b^8c^{16}a^8 + [ac^2b]^8 \qquad (3)$$

The symmetrical version of the code becomes

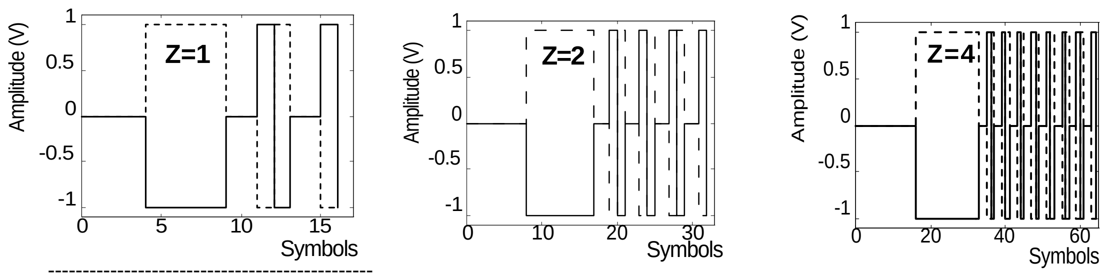
$$S_{FSK\text{-}MTS} = \mathbf{O},\ S_1S_2^{\,4}\ ,\ c^8a^8,\ ac^2b \qquad (4)$$

where **O** indicates odd symmetry, $S_1 = c^8a^8$ and $S_2 = ac^2b$.

The measurement code for this set of FSK MTS in a general form using the zoom factor, Z, is

$$S_{FSK\text{-}MTS\text{-}Z} = \mathbf{O},\ S_1S_2^{\,2Z}\ ,\ c^{4Z}a^{4Z},\ ac^2b \qquad (5)$$

where Z = 1, 2, 3, 4, etc. The lower set of dominant harmonics is 1, 2, 4 while the upper set is now 8Z, 16Z. A total number, 32Z, of symbols is required. The frequency range with Z=1 is extended by an additional octave for each increase in Z by a factor of 2 giving Z = 2, 4, 8, etc. When Z=4, this FSK MTS design covers 6 octaves using the dominant harmonics 1, 2, 4, and 32, 64 with 128 symbols. The DM toolbox [2] is used to give the MIP and the dominant harmonics information, which are given in Figure 6.




| HAR | E(k) | PHASE | P(k) |
|---|---|---|---|
| 1 | +0.545 | +90.000 | +29.68 |
| 2 | +0.318 | +90.000 | +10.13 |
| 4 | +0.318 | -90.000 | +10.13 |
| 8 | +0.318 | +90.000 | +10.13 |
| 16 | +0.318 | +90.000 | +10.13 |

SELECTED POWER = 76.62 %
PARSEVAL POWER = 0.500 W

| HAR | E(k) | PHASE | P(k) |
|---|---|---|---|
| 1 | +0.497 | +90.000 | +24.72 |
| 2 | +0.318 | +90.000 | +10.13 |
| 4 | +0.318 | -90.000 | +10.13 |
| 16 | +0.318 | +90.000 | +10.13 |
| 32 | +0.318 | +90.000 | +10.13 |

SELECTED POWER = 65.24 %
PARSEVAL POWER = 0.500 W

| HAR | E(k) | PHASE | P(k) |
|---|---|---|---|
| 1 | +0.474 | +90.000 | +22.43 |
| 2 | +0.318 | +90.000 | +10.13 |
| 4 | +0.318 | -90.000 | +10.13 |
| 32 | +0.318 | +90.000 | +10.13 |
| 64 | +0.318 | +90.000 | +10.13 |

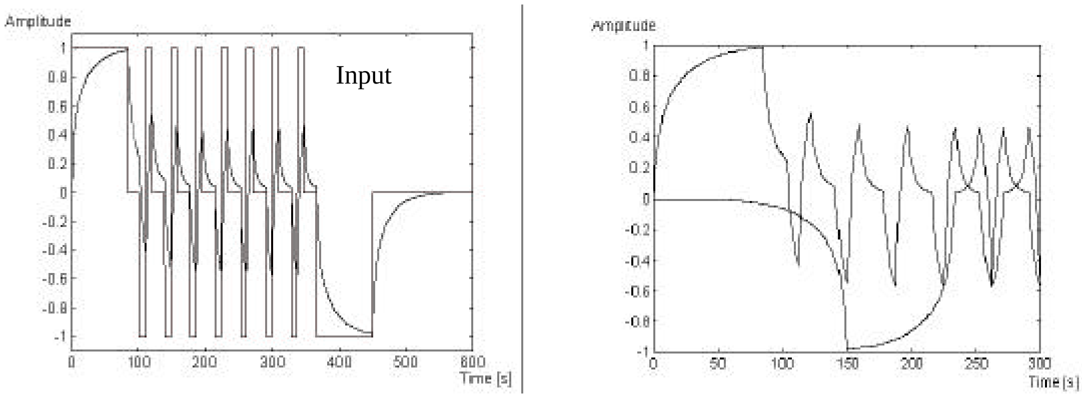
SELECTED POWER = 62.95 %
PARSEVAL POWER = 0.500 W

**Figure 6.** MIP and dominant harmonic information for a set of symmetrical FSK MTS signals (Z=1, 2 & Z=4) with MC **O**, $S_1S_2^{\,2Z}$ , $c^{4Z}b^{4Z}$, $bc^2a$

This Left Hand Side (LHS) and Right Hand Side (RHS) of the symmetrical code and corresponding MIP contain all of the energy of the expected dominant harmonics according to the FSK design. However in addition, the LHS also contains almost all of the fundamental energy. While the magnitude and phase of the FSK harmonics are always the same, the magnitude and phase of the fundamental must be calculated each time Z is changed.

These FSK signals have the ability to examine and extract information from two parts of a system frequency response. They are all compact as required by the identification source coding theorem while the FSK design captures the highest frequency information according to the identification channel coding theorem.

Figure 7(a) shows the time waveform for the input signal and output of a simulated RTD sensor. The corresponding MIP which may be used for condition monitoring of both a low and a high set of frequencies is given in figure 7 (b). To remove the switch-on transient, an asymmetrical form of the signal with all the c symbols at the end of the MC is used. The information obtained by this design and its application are still under investigation.




(a) (b)

**Figure 7.** Monitoring a simulated temperature sensor using a frequency shift keyed signal

## 5 CONCLUSIONS

An identification design based on coding theory ensures that a signal, which is described by the minimum number of symbols, concentrates its energy on the aspect of the channel frequency response information that is required. These new shift keyed signals can allow an immediate and accurate evaluation of the frequency response information during the first period of the signal. The availability of modern PC based instrumentation like Lab View, and others in the development stage, must revive an interest in perturbation signals for multifrequency testing in measurement and control laboratories. Strathclyde compact shift keyed sequences add powerful new interrogation signals for the microcomputer evaluation of frequency response estimates. They provide a new design philosophy that fills the gap in the knowledge between the extremes of the squarewave and a PRBS signal. This will provide the opportunity for intelligent on-line action by a measurement system in a wide variety of applications.

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**AUTHORS:** Dr. I.A. HENDERSON, Dr. J. MCGHEE, ICC, University of Strathclyde, 50 George Street, Glasgow G1 1QE, Scotland, Phone Int: +141 931 5512, Fax Int: +141 548 4203
E-mail: ian@henderland-gate.freeserve.co.uk
Dr. L. JACKOWSKA-STRUMILLO, Computer Engineering Department, Technical University of Lodz, Al. Politechniki 11, 90-924 Lodz, Poland, Phone Int: + (48 42) 631 26 89, Fax Int: +(48 42) 631 27 50, E-mail lidia_js@kis.p.lodz.pl