ELIMINATION OF THE CONTACT BOUNCE PHENOMENON

By

S. DOMONKOS and GY. MADARÁSZ

Department for High Voltage Engineering
and Electrical Apparatus, Technical University, Budapest

(Received October 18, 1968)

Presented by Prof. Dr. J. EISLER

Introduction

A fundamental problem of electrical apparatus development is the reduction or elimination of contact bouncing. Several papers were published recently [2] [3] [4] [6] [7] [8] on the study of bouncing between spherical and plate contacts. The total number and duration of bounces was determined in case of varying parameters.

Nevertheless, the question arises: what are the conditions for complete bounce suppression? An equation, given by KESSELRING [9] determines, on the basis of energies concerned, the necessary contact biasing force.

By formulating the equation of mechanical oscillation, it was attempted to find an approximate solution, with material constants to be easy determined. To this end the usual velocity conditions and contact materials of the contactors were taken into consideration.

1. The equation of oscillation for the linear mechanical model

Fig. 1 shows the kinetic model of the contacts. The stationary contact is an infinite plate, while the moving one is a sphere of mass m. The material of the two contacts is identical.

Symbols:

- M concentrated mass in motion of the operating system
- m mass of the spherical contact
- C_1 spring constant biasing the spherical contact;
- C common spring constant of sphere and plate;
- K_s damping coefficient of the contact material, proportional to the velocity;
- x co-ordinate of the sphere;
- y co-ordinate of the operating system.

The moving contact, at the instant $t = 0$ collides with the stationary contact at a velocity v_0.

In the following the movement of the contacts during the impact will be studied.

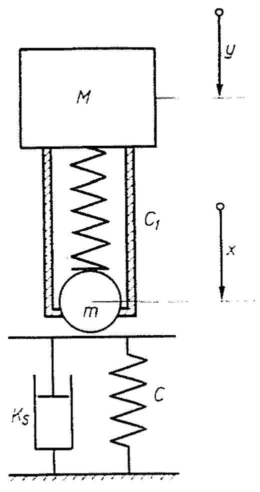

Fig. 1. The kinetic model of the contact

The model in Fig. 1 can be described by the following system of differential equations:

$$m\frac{d^2x}{dt^2} = -Cx - K_s\frac{dx}{dt} + F_e + mg + C_1(y-x) \tag{1.1}$$

$$M\frac{d^2y}{dt^2} = -C_1(y-x) - F_e + Mg \tag{1.2}$$

In these equations F_e is the biasing force of the spring, and g is the acceleration due to gravity.

Initial and boundary conditions are:

at $t=0:\ x=0,\ y=0,\quad \frac{dx}{dt}=\frac{dy}{dt}=v_0$

and

at $t=\infty:\ x=\frac{M+m}{C}g$

$$y = x + \frac{Mg - Fe}{C_1}$$

provided, that C, C_1 and K_s are constant.

The solution of the system of equations (1.1) and (1.2) gives the displacement as a function of time. In order to ease the solution, a simplification was used.

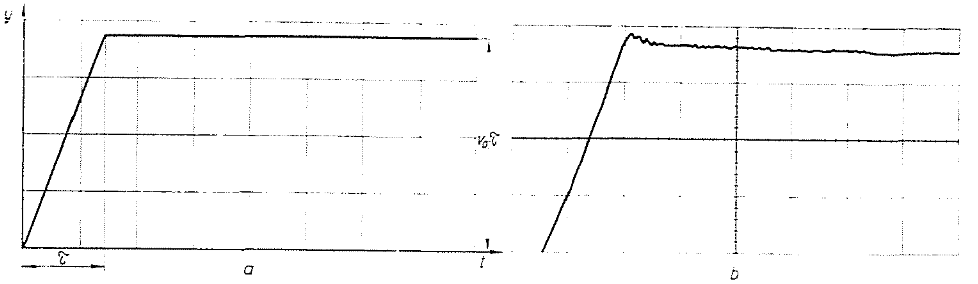

Fig. 2. The movement of the operating mechanism vs. time from the instant of contact, on the basis of: a) approximation; b) measurement

The $y = y(t)$ function describing the movement of the operating system is assumed to be known. Fig. 2 shows its form as assumed and determined on the model. In mathematical form:

$$y = 1(t) \cdot v_0(t) - 1(t - \tau) \cdot v_0(t - \tau) \tag{1.3}$$

where $y_1 = v_0\tau$ is the distance taken by the spring after the first contact.

Substituting Eq. (1.3) into Eq. (1.1), and keeping in mind that $C \gg C_1$, we have:

$$m \frac{d^2x}{dt^2} + K_s \frac{dx}{dt} + Cx = 1(t)\,F(t) + C_1 1(t)\,v_0 t - 1(t - \tau)\,v_0(t - \tau) \tag{1.4}$$

In practical cases $C > \frac{K_s^2}{4m}$ is always true for the contact materials, resulting in a periodical solution for the differential equation. The result, namely the function $x(t)$ describes the movement of the sphere during the impact.

The solution of Eq. (1.4) is:

if $t < \tau$, then

$$x(t) = A_1 e^{-\alpha t} \sin \omega t + A_2 e^{-\alpha t} \cos \omega t + A_3 t + A_4 \tag{1.5}$$

and if $t > \tau$, then

$$x(t) = B_1 e^{-\alpha t} \sin \omega t + B_2 e^{-\alpha t} \cos \omega t + B_3 \tag{1.6}$$

In these equations ω is the angular frequency of the mechanical oscillation and α is the damping coefficient.

$$\omega = \sqrt{\frac{C}{m} - \alpha^2}; \qquad \alpha = \frac{K_5}{2m}$$

Eqs. (1.5) and (1.6) give identical results for $t = \tau$. After rearranging these equations, we have:

$$x(t < \tau) = Ae^{-\alpha t} \sin(\omega t - \varphi) + A_3 t + A_4 \tag{1.7}$$

and

$$x(t > \tau) = Be^{-\alpha t} \sin(\omega t - \varphi) + B_3 \tag{1.8}$$

The motion described by the above equations is a damped oscillation, superimposed on the deformation caused by external forces (Fig. 3). Eqs. (1.7)

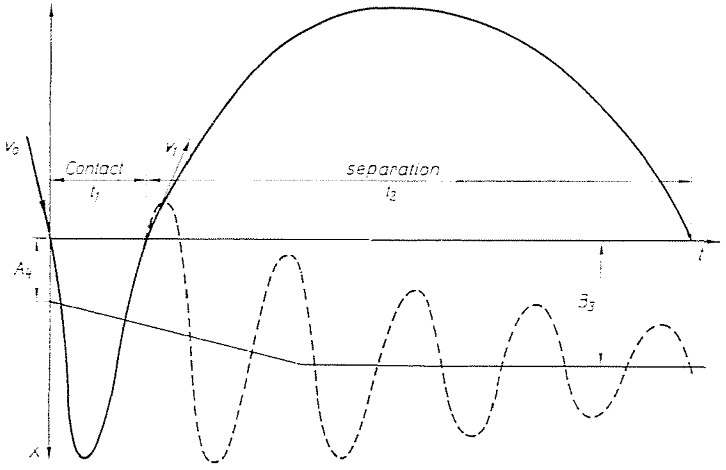

Fig. 3. The function, describing contact movement

and (1.8) are valid, up to $x > 0$, that is the sphere contacts the plate. When the sphere leaves the plate, or "bounces", then its movement will follow other laws of physic.

Determination of the condition of bouncing

If the function $x(t)$, describing the motion during the contact is always positive, no bouncing occurs. For usual contact materials and velocity conditions in contactors, it can be said, that

$$T = \frac{2\pi}{\omega} \ll \tau$$

which means, that the period T of the periodic term is much less than the time due to the distance taken by the spring after the first contact. It is reasonable therefore to study only Eq. (1.7), which after rearrangement becomes:

$$-Ae^{-\alpha t}\sin(\omega t-\varphi)<A_3t+A_4 \tag{1.9}$$

Conditions of the elimination of bouncing can be determined by investigating the first extreme value at the left side of Eq. (1.9).

Though it describes an exponentially damped sinusoidal oscillation, the error will be negligible, when only the extreme value of the sine function is taken into account. From the condition

$$\sin(\omega t-\varphi)=-1$$

the argument of the extreme value is:

$$t_m=\frac{\varphi+1{,}5\,\pi}{\omega} \tag{1.10}$$

Substituting it in (1.9) we have:

$$Ae^{-\alpha t_m}<A_3t_m+A_4 \tag{1.11}$$

Substituting the constants:

$$\sqrt{\left(\frac{v_0}{\omega}\right)^2+\left(\frac{F}{C}\right)^2}\cdot e^{-\alpha t_m}<\frac{v_0C_1}{C}\,t_m+\frac{F}{C}\approx\frac{F}{C} \tag{1.12}$$

The spring force increase due to the distance taken after the first contact during t_m is usually small in comparison to the bias and its neglection adds to the safety. On the other hand according to common practice, the frequency of vibration is so high that no significant growth of force takes place until the first maximum.

After rearranging Eq. (1.12), the criterion of the elimination of bouncing is:

$$\frac{v_0}{F}<\frac{\omega}{C}\sqrt{e^{2\alpha t_m}-1} \tag{1.13}$$

where

$$t_m=\frac{\operatorname{arc\,tg}\dfrac{F}{v_0}\dfrac{\omega}{C}+1.5\,\pi}{\omega} \tag{1.14}$$

From Eqs. (1.13) and (1.14) the conclusion can be drawn that the elimination of bouncing is determined by the ratio $\frac{v_0}{F}$. It must be noted, however, that the term $\frac{v_0}{F}$ is included in the formula (1.14) too, but this being an unequality, it cannot be given in explicit form.

The approximate solution is easy to compute. There remain three problems:

a) to measure the material constants of various contact materials,

b) to compute the necessary biasing force from Eq. (1.13) for the above material constants. This was done by an analogue computer.

c) to check the validity of the approximate equation in order to justify the neglections.

2. The determination of the constants by measurements

In numerical computations it is necessary to know not only the biasing force F_e, the spring constant C_1, mass m and impact velocity v_0, but also the common spring constant C of the contact material and the damping coefficient K_s, proportional to velocity.

The common spring constant C and the damping coefficient K_s can be determined in the knowledge of the natural angular frequency ω and damping coefficient α using the following equations:

$$\omega = \sqrt{\frac{C}{m} - \alpha^2}$$

$$\alpha = \frac{K_s}{2m}$$

Several measurements were made to determine the angular frequency ω and

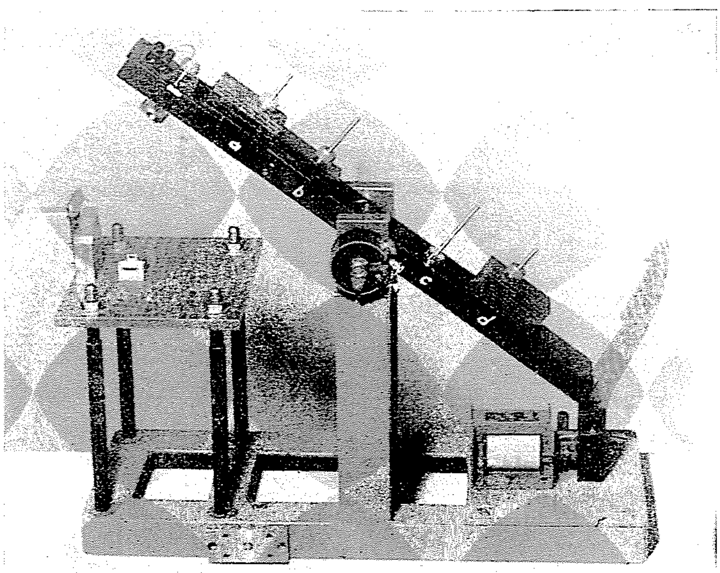

Fig. 4. Test device

damping coefficitent α. The measuring apparatus, Fig. 4, was designed in accordance with the model in Fig. 1.

To determine α and ω, very light and weakly biased spring was used. Due to the soft spring characteristic of the spring (low spring constant C_1) and the low biasing force, static deformation, on which the oscillation is superimposed,

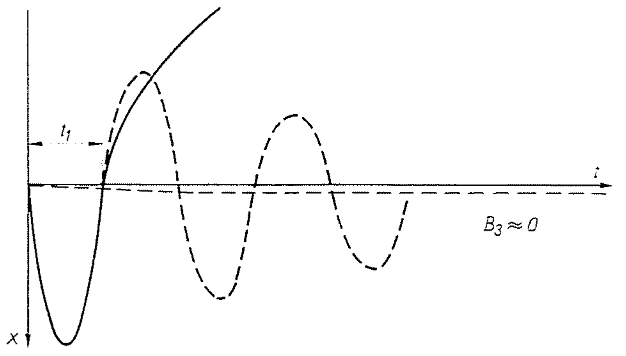

Fig. 5. Contact movement, when loaded by a low spring force

will be negligible (Fig. 5). Hence, in Eq. (1.5) the values A_2, A_3 and A_4 are negligible. The equation of motion during the contact period is

$$x(t) \approx A_1 e^{-\alpha t} \sin \omega t \tag{2.1}$$

After differentiation we have the velocity

$$\frac{dx}{dt} = -\alpha A_1 e^{-\alpha t} \sin \omega t + \omega A^1 e^{-\alpha t} \cos \omega t \tag{2.2}$$

Replacing into Eqs (2.1) and (2.2) $t = 0$, $\frac{dx}{dt} = v_0$, $x = 0$ pertaining to the instant of contact, and $t = t_1$,

$\frac{dx}{dt} = v_1$, $x = 0$, pertaining to the instant of bouncing, we have

$$\alpha = \frac{1}{t_1} \ln \frac{v_0}{v_1} \tag{2.3}$$

and

$$K_s = \frac{2m}{t_1} \ln \frac{v_0}{v_1} \tag{2.4}$$

On the other hand, the angular frequency of the oscillation can be determined from the duration of the contact, t_1, because according to the above conditions being about the half of the period T. Thus

$$\omega = \frac{\pi}{t_1} \tag{2.5}$$

In the knowledge of α and ω the common spring constant of the contact material can be determined:

$$C = m(\omega^2 + \alpha^2) \approx m\omega^2 \tag{2.6}$$

In order to determine the constants several oscillograms of the duration of contact and separation were taken. One of them is shown in Fig. 6. Impact

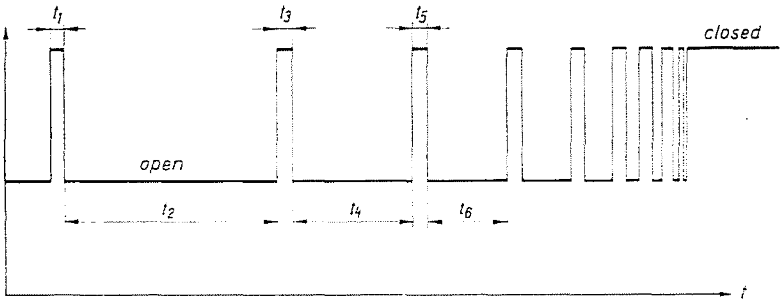

Fig. 6. Times of contact (t_1, t_3, t_5) and separation (t_2, t_4, t_6) upon switching on

velocity was controlled by the weights attached to the arms of the test device in Fig. 4.

Impact velocity was measured by

1. high speed photography;
2. potentiometric displacement transducer;
3. inductive displacement transducer.

The bouncing velocity v_1 was determined from the separation time t_2 after contact by the equation

$$v_1 = \frac{F + mg}{\sqrt{mC_1}} \operatorname{tg} \frac{t_2}{2} \sqrt{\frac{C_1}{m}} \tag{2.7}$$

Eq. (2.7) is derived from the equation of motion of the separated moving contact.

The equation of motion and its solution are essentially identical to those published by ERK, and FINKE [2].

The validity of the method of computation was checked by means of an inductive displacement transducer. In these measurements iron was the material of the contacts. The principle of measurement is shown in Fig. 7.a. From the oscillogram (Fig. 7.b) both the impact and separation velocities and separation time t_2 can be determined, on the basis of which the equation (2.7) can be checked.

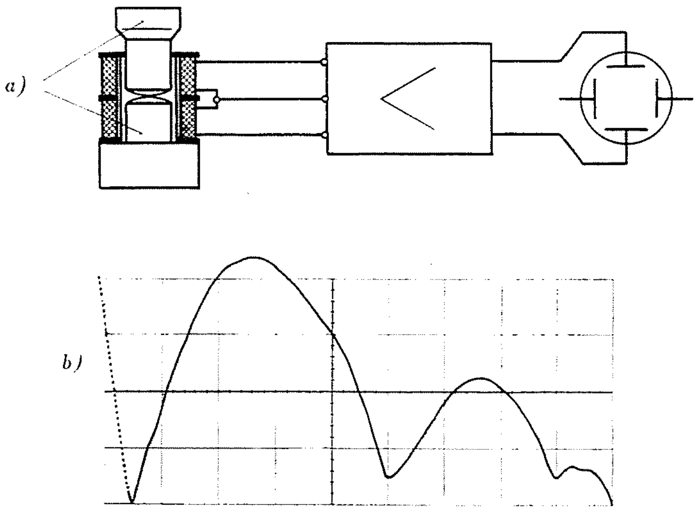

Fig. 7. a) The measurement of contact movement by inductive displacement transducer; b) Contact movement vs. time

From the measurements on bouncing the following constants can be determined:

$$\text{damping coefficient } \alpha \left[\frac{1}{\text{sec}}\right]$$

	Ag 1000	Ag CdO 90/10
$r = 5$ mm sphere to plate contact	3300	3300
$r_1 = r_2 = 25$ mm sphere to sphere contact	1900	2400

$$\text{angular frequency } \omega \left[\frac{1}{\text{sec}}\right]$$

	Ag 1000	Ag CdO 90/10
$r = 5$ mm sphere to plate contact	$12 \cdot 10^3$	$13 \cdot 10^3$
$r_1 = r_2 = 25$ mm sphere to sphere contact	$6.4 \cdot 10^3$	$7.4 \cdot 10^3$

The values of the constants show some dispersion as a function of velocity. The values indicated above are the means of the measured data.

3. Computation and measurement of the elimination of bouncing

If constants $\varkappa$ and ω are known, the ratio $\frac{F_{kr}}{v_0}$, pertaining to the elimination bouncing can be computed from Eqs (1.13) and (1.14).

The values of $\frac{F_{kr}}{v_0}\left[\frac{\text{kp sec}}{\text{m}}\right]$

	Ag 1000	Ag CdO 90/10
$r = 5$ mm		
sphere to plate contact	9.9	11.6
$r_1 = r_2 = 25$ mm		
sphere to sphere contact	4.63	4.63

For the impact velocity $v_0 = 0.55$ m/sec the following spring biasing forces were computed to completely suppressed of bouncing

F_{kr}[kp]

	Ag 1000	Ag CdO 90/10
$r = 5$ mm		
sphere to plate contact	5.5	6.4
$r_1 = r_2 = 25$ mm		
sphere to sphere contact	2.6	2.6

In order to check the computation, it was run on an analogue computer The computer model of Eqs (1.7) and (1.8) describing the motion of the contacts is shown in Fig. 8. Solutions for various biasing forces are shown in Fig. 9.

It is to be noted, that by increasing the biasing force, a value (F_{kr}) is reached, for which no gative deformation (x) of the stationary contact takes place any more, henceno bouncing occurs.

Consequently, the biasing force, necesarry to eliminate contact bouncing, can be directly determined by means of an analog computer. Computer results

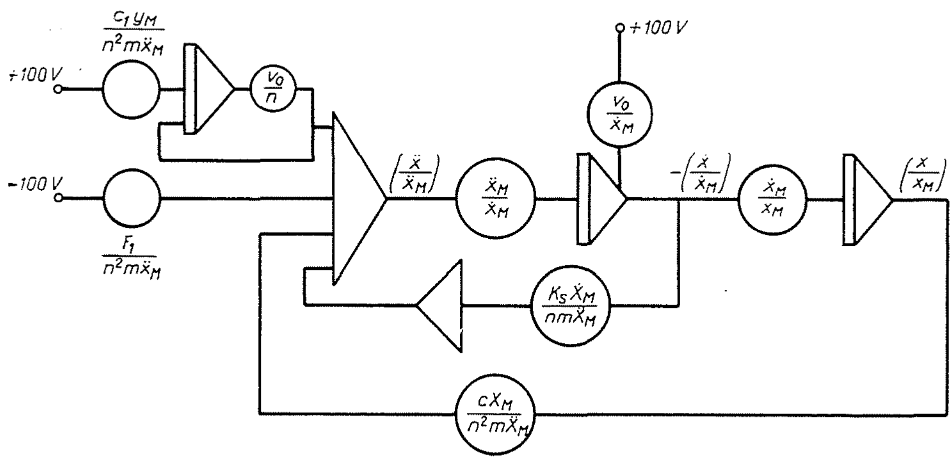

Fig. 8. Analogue model simulating contact movement during switching on

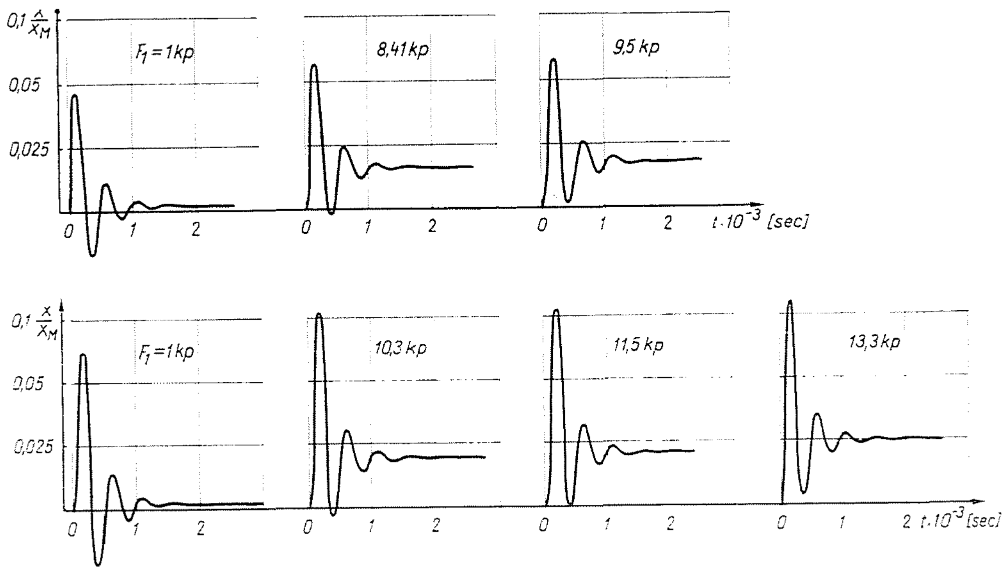

Fig. 9. Solutions given by the analogue computer

for the previous case are:

F_{kr}[kp]

$r = 5$ mm	Ag 1000	Ag CdO 90/10
sphere to plate contact	5.26	6.1
$r_1 = r_2 = 25$ mm		
sphere to sphere contact	2.7	2.61

Results have been checked by measurements on the test device in Fig. 4, aimed at determining the limiting case of bouncing.

Bouncing times were oscillographed for gradually increasing biasing forces. In this way the biasing forces for which bouncing phenomena just appeared and disappeared could be determined.

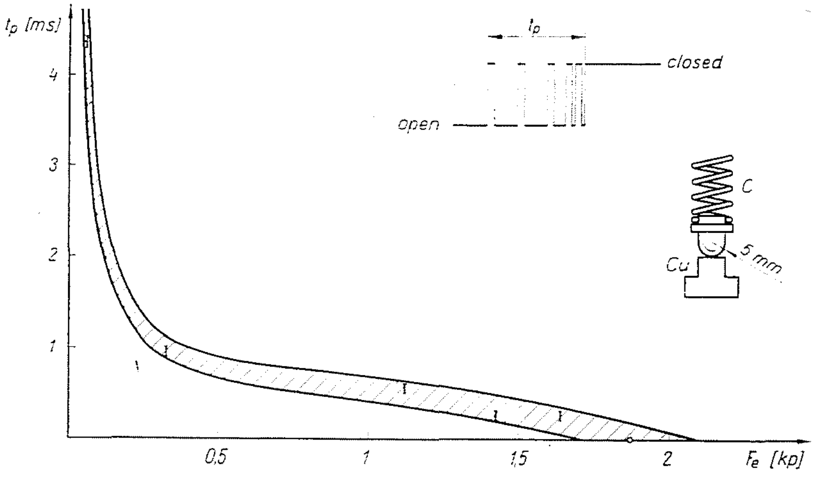

Fig. 10. The most probable bouncing time values (t_p) vs. biasing force

The measurement data are as follows:

	F_e [kp] Ag 1000	Ag CdO 90/10
$r = 5$ mm sphere to plate contact	5.7—6.1	5.7
$r_1 = r_2 = 25$ mm sphere to sphere contact	2.7—3.1	2.6—3

These data show a fair agreement with the computed ones.

The measured bouncing time values for identical velocities and biasing forces are rather widely scattered. This fact made the check of the computation method unreliable, therefore further measurements and development of the measuring technique were required.

Instead of oscillography, a high precision electronic digital equipment was used to measure the sum of bouncing times, which enabled us to take a great number of measurements rapidly.

The sum of bouncing times (t_p) was measured by gradually increasing biasing force (Fig. 10). The most probable values among 20 measurements each are shown in Fig. 10 as a function of the biasing force. With gradually increasing biasing forces the number of zero bouncing times increased. It is evident, that by further increasing the biasing force, zero bouncing time can be reached in 100% of the measurements. Zero bouncing times were taken for measurements 50% of the data were zero. Consequently that given force was regarded as the critical biasing force, with which contact bouncing could be eliminated at a high probability. The measurements were taken with a velocity $v_0 = 0.406$

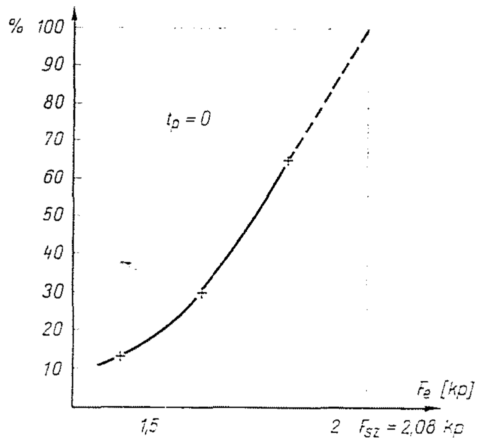

Fig. 11. Relative frequency of zero bouncing times ($t_p = 0$) vs. biasing spring force; $F_{comp} = 2.08$ kp is the computed value

m/sec, while the mass of the moving contact was $m = 0.918 \cdot 10^{-3}$ [kp sec^2/m]. The spring constant of the biasing spring was:

$$C = 127.5 \text{ [p/mm]}$$

The method, described in chapter 2, produces the constants, which in this case were found to be $\alpha = 12.43 \cdot 10^3$ [1/sec] and $\omega = 33.9$ [kHz]. Substituting these data in Eqs (1.13) and (1.14) the biasing force for which bouncing is suppressed is found to be $F_{.} = 2.08$ [kp]. Comparing this value with the one, determined from the measurement on the basis of 50% probability of zero bouncing time ($F_e = 1.87$ kp), 10% error is observed, but the computed value is in error on the safe side. Plotting the relative frequency of the occurrence of zero bouncing times ($t_p = 0$) as a function of the biasing force (Fig. 11), it is found, that the value of about 98% of the relative frequency belongs to the computed value.

On the basis of the above results, the method of computation described in this paper can be effectively used to determine the conditions of the elimination of bouncing.

In Fig. 10, where bouncing time vs. biasing force is shown, may be noted, that at small forces bouncing time rapidly decreases, but at higher forces its change is much smaller.

Apart from the fact that bouncing can be theoretically and practically completely eliminated, a question of technical-economical nature arises, namely: how long is it worth trying to decrease bouncing time? When increasing the spring force, an operating mechanism of ever more robust design is needed, which consequently increases the weight and the price of the contactor. Without attempting here a detailed analysis of the problem, it may be said, that from a technical-economical aspect a bouncing time of about 1 msec is the lower limit, which is worth trying to attain.

The effect of current on bouncing

In the analysis given above cases were studied where the contacts switched on practically without current. The problem is now what is the effect of current up to about 1200 A, switched on by the contactors, on bouncing?

Two factors must be taken into account here. The electrodynamical repulsion forces, described in great detail in the relevant literature, increase bouncing tendency. The thermal effect of the current results in a decreased tendency for bouncing, due to the heating and softening of the contacts. Our measurements on contactor contacts in the range of 100 to 1200 A showed a definite decrease of bouncing time. From all of this it follows, and this statement can be justified by computations, that in this current range the thermal effect of the current, which decreases bouncing, is predominant over the small repulsive force. The effect of the repulsive force is further decreased by peaks on the contact surfaces, deformation of which causes dissipation of kinetic energy, when switched on.

Summary

Sphere to plate contact bounce phenomenon has been studied in velocity and force conditions typical for low-voltage contactors. On the basis of literature data, an equation of mechanical oscillation is constructed and solved approximately. An equation is derived to determine the spring force necessary for complete bounce suppression. The constants for this equation were determined by measurements on a test model. An analogue computer was used for the computations.

In order to prove the theory, a great number of measurements on bouncing were taken with various velocities and spring forces. Bouncing time was recorded by a digital instrument. With increasing spring forces bouncing time gradually diminished until its complete elimination. Measured and computed data showed a fair agreement. As a last step, the degree of technically and economically justifiable reduction of bouncing time is investigated.

References

1. Babikov, M. A.: Villamos készülékek, Nehézipari Könyvkiadó, Budapest, 1953.
2. Erk, A.—Finke, H.: ETZ. A. **86**, 129 (1965).
3. Erk, A.—Finke, H.: ETZ. A. **86**, 297 (1965).
4. Dzierzbicky, A.—Walczuk, E.: Einfluß der Veränderlichkeit der Stoßzahl auf die Berechnungsergebnisse der Kontaktabhebungen. Kontakte in der Elektrotechnik 3. Kontakttagung Berlin 1967.
5. Goldsmith, W.: Impact. The Theory and Physical Behaviour of Colliding Solids. Edward Arnold, London, 1960.
6. Molnár, I.: Elektrotechnika **59**, 53 (1966).
7. Barkan, P.: IEEE. Transactions **86**, 231 (1967).
8. Bron, O. B.: Elektricheskaya duga v apparatah upravleniya. Gosenergoisdat, Moscow—Leningrad, 1954.
9. Kesselring, F.: Theoretische Grundlagen zur Berechnung der Schaltgeräte. W. de Gruyter Berlin, 1950.

Dr. Sándor Domonkos
György Madarász

Budapest XI, Egri József u. 18. Hungary