United States Patent [19]

Nash

[11] **3,827,809**

[45] **Aug. 6, 1974**

[54] **CIRCUITS FOR DERIVING A COMMON OUTPUT SIGNAL FROM A PLURALITY OF AMPLIFIERS IN APPARATUS FOR DETECTING BLEMISHES IN SHEET MATERIAL**

[76] Inventor: **Paul Nash,** 44 Westbourne Ter., London, England

[22] Filed: **May 11, 1973**

[21] Appl. No.: **359,511**

[30] **Foreign Application Priority Data**

May 12, 1972 Great Britain 22393/72
May 19, 1972 Great Britain 23711/72

[52] **U.S. Cl.** **356/200,** 250/562
[51] **Int. Cl.. G01n 21/16,** G01n 21/32, G01n 21/30
[58] **Field of Search** 250/562; 356/200

[56] **References Cited**

UNITED STATES PATENTS

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Primary Examiner—James W. Lawrence
Assistant Examiner—T. N. Grigsby
Attorney, Agent, or Firm—Browdy and Neimark

[57] **ABSTRACT**

A circuit for combining the outputs of several amplifiers, through an array of diodes, so that the combined output has a noise content whose amplitude is less than that of the individual amplifier outputs. The circuit is described as part of an inspection system for detecting blemishes in sheet material flowing past a series of photo-sensitive devices, the amplifiers receiving the outputs of the photo-sensitive devices.

15 Claims, 41 Drawing Figures

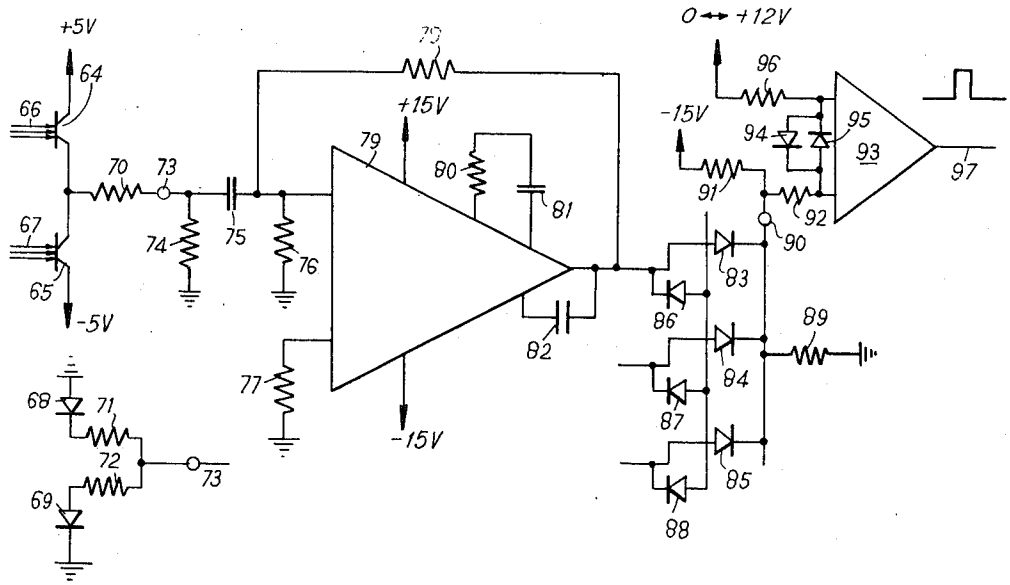


FIG. 1.

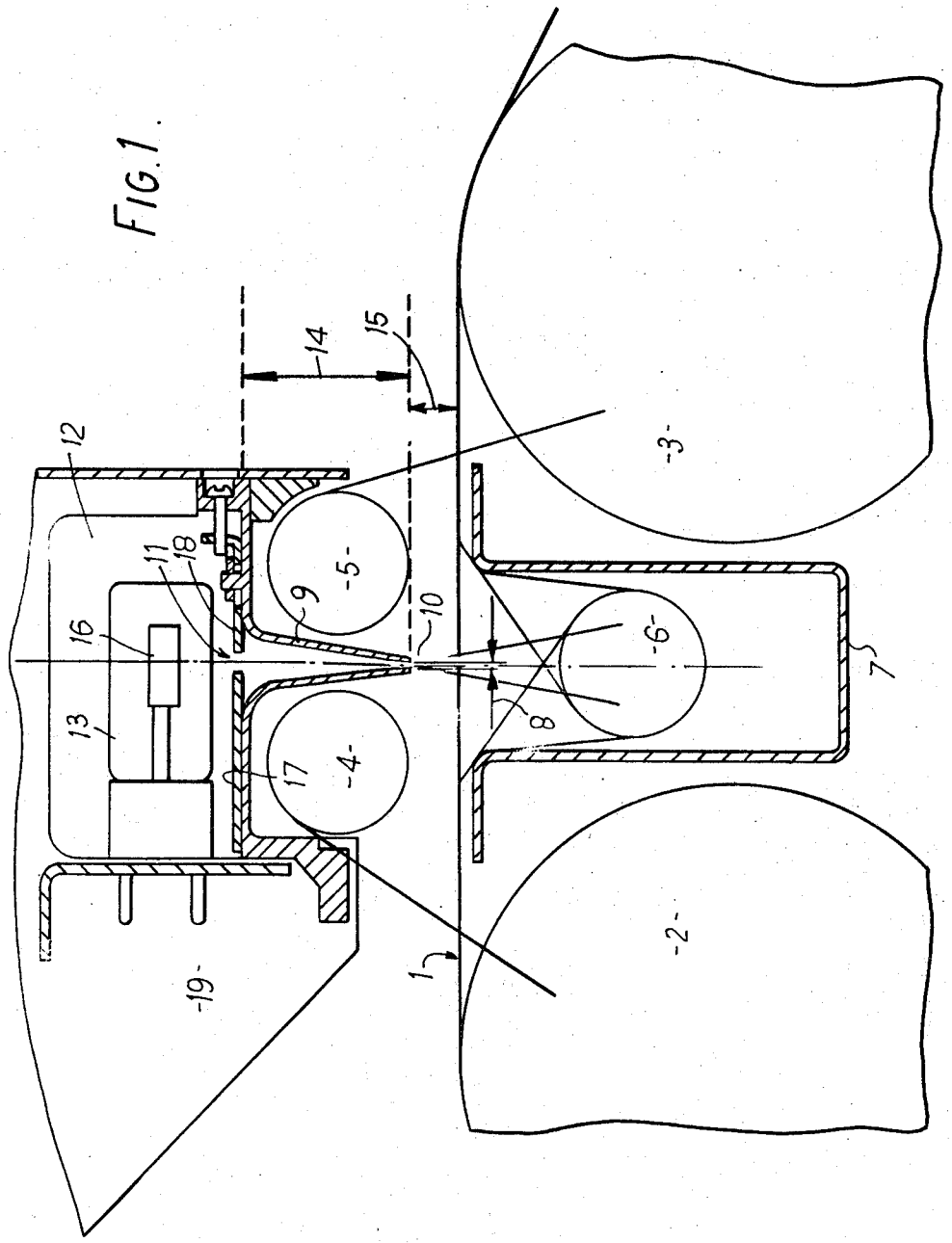
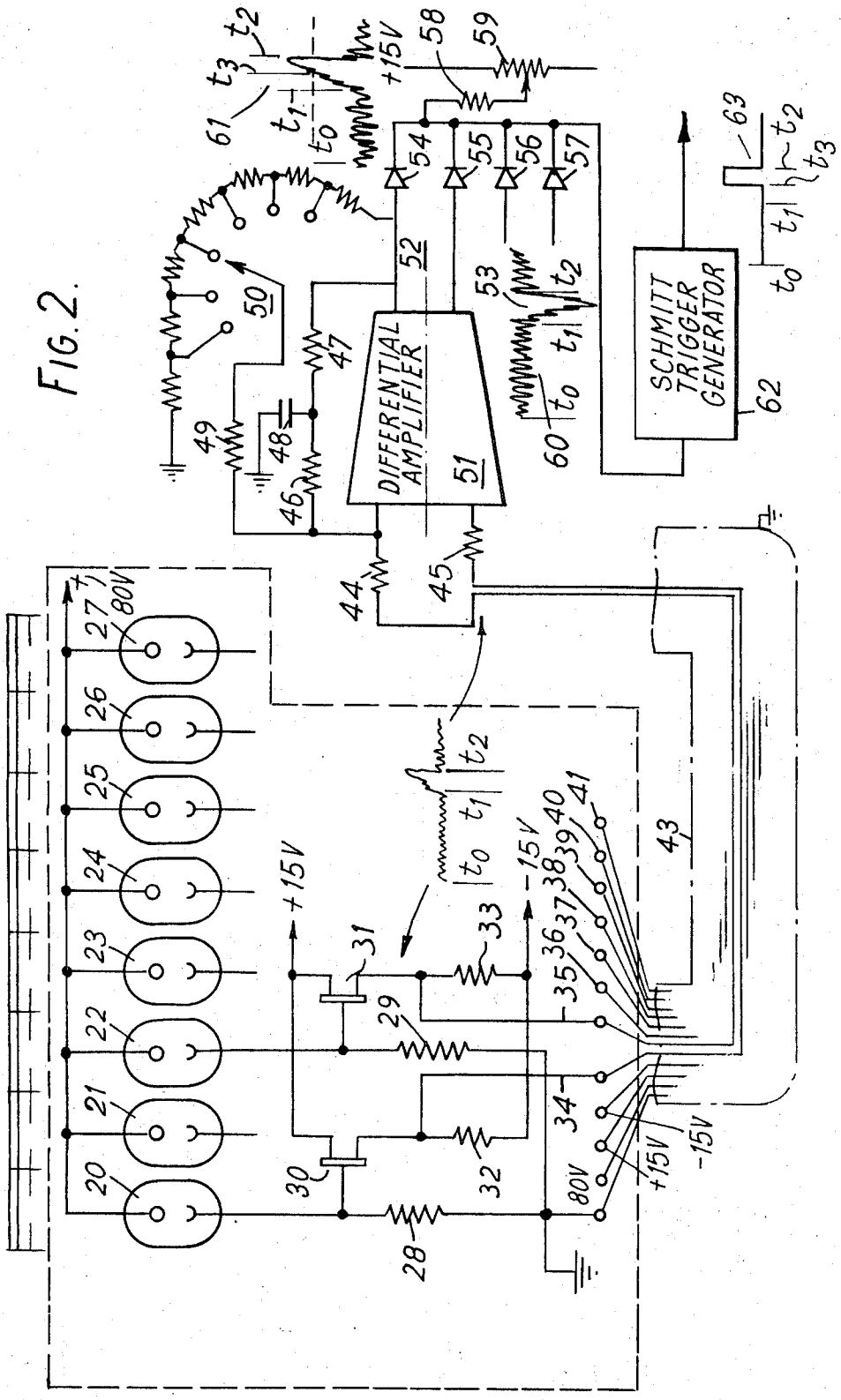


FIG. 2.


DIFFERENTIAL AMPLIFIER
SCHMITT TRIGGER GENERATOR
+15V
-15V
80V

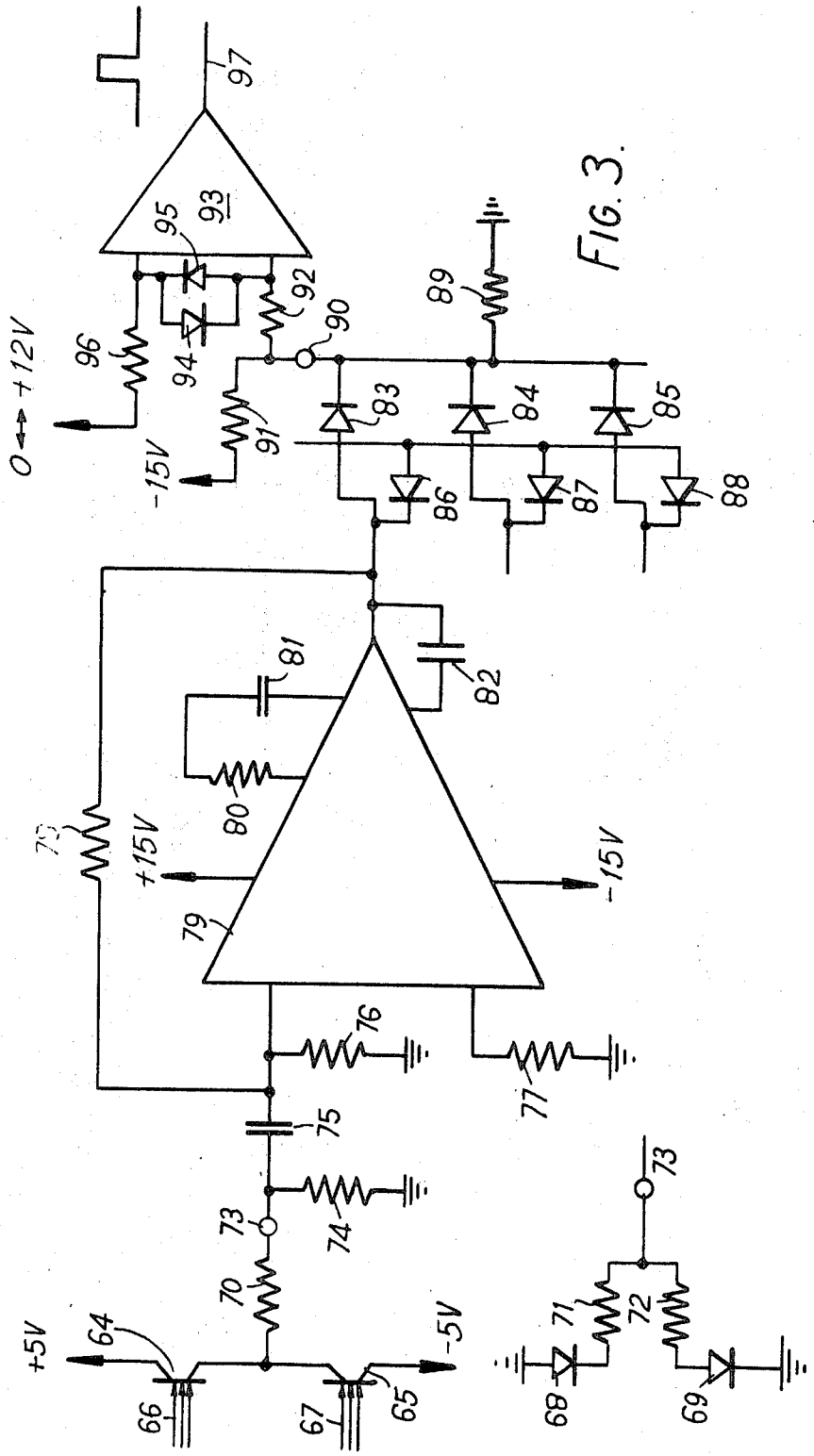

97
93
95
92
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89
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91
0 ↔ +12V
-15V
83
84
85
86
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88
81
82
80
78
+15V
79
-15V
76
77
75
73
74
70
+5V
64
-5V
66
67
65
73
71
72
68
69

FIG. 3.

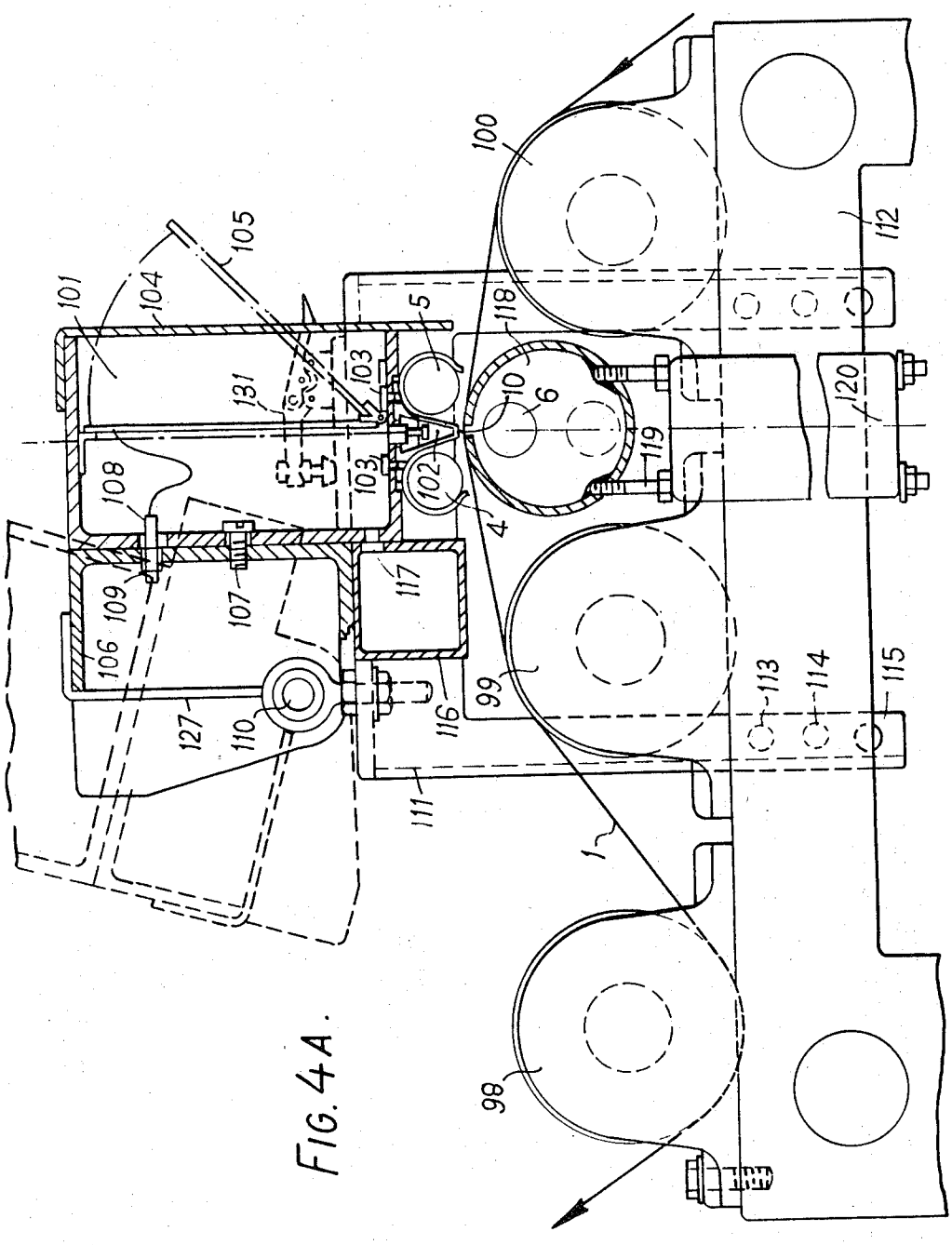

100
105
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131
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118
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6
120
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127
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98

FIG. 4A.

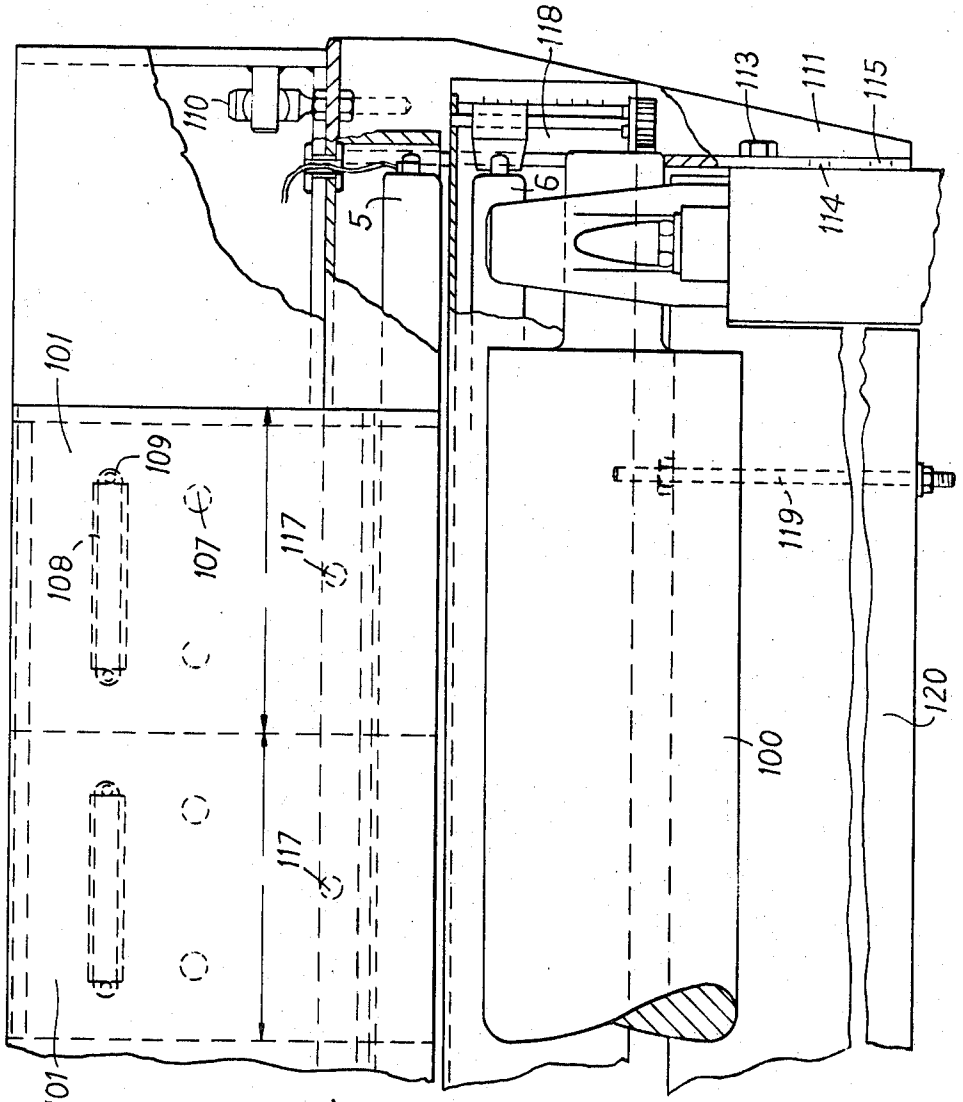

118
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FIG. 4B.

FIG. 4C.

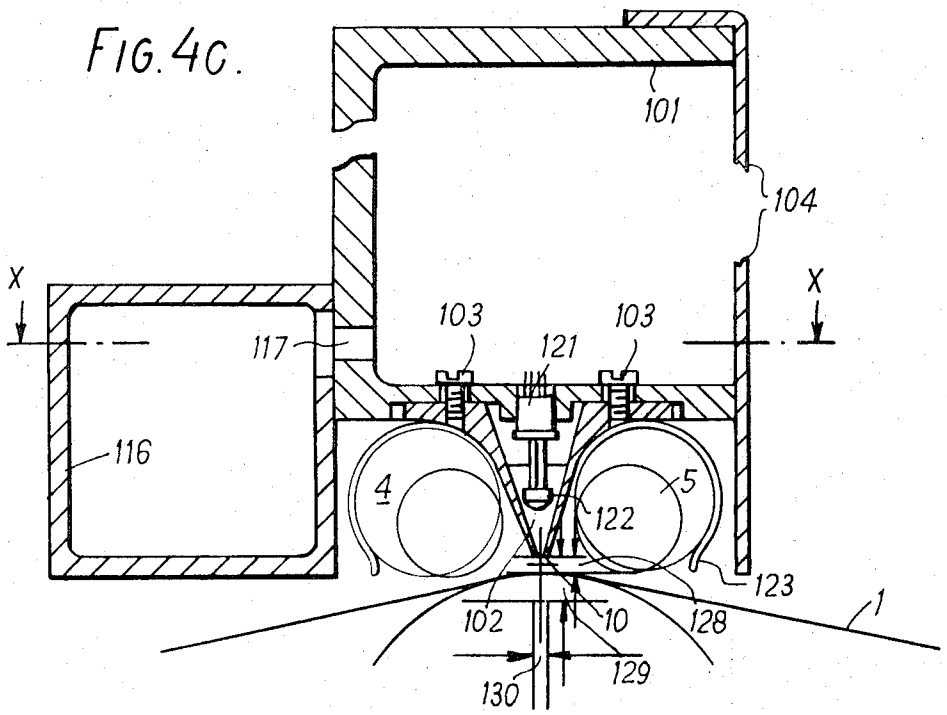
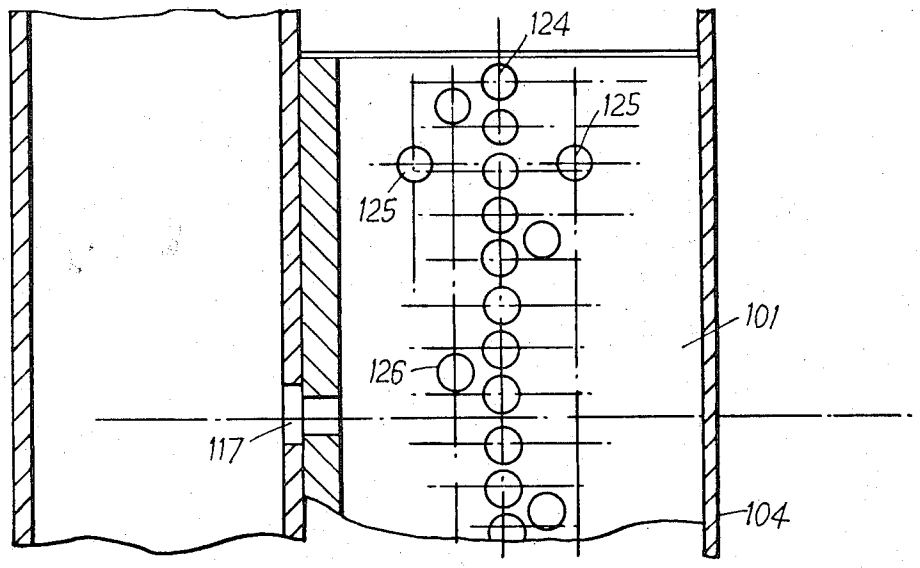

101
104
X
X
103
103
121
117
116
4
5
122
123
102
10
128
1
129
130

FIG. 4D.


124
125
125
101
126
117
104

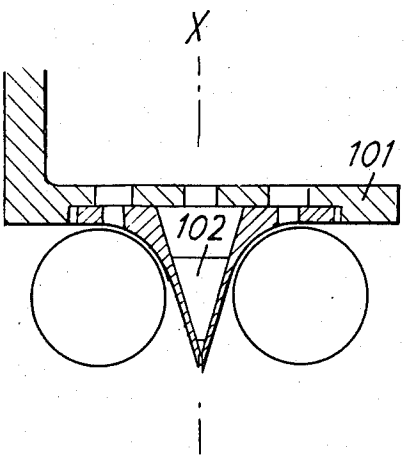


FIG. 4C/D

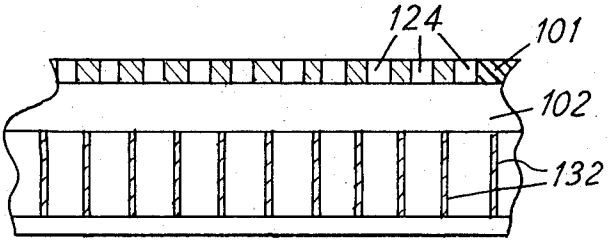


FIG. 4E.

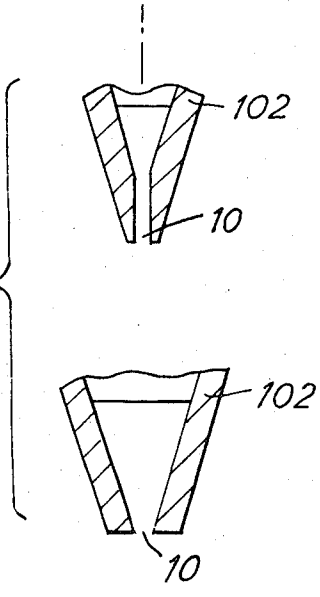


FIG. 4F.

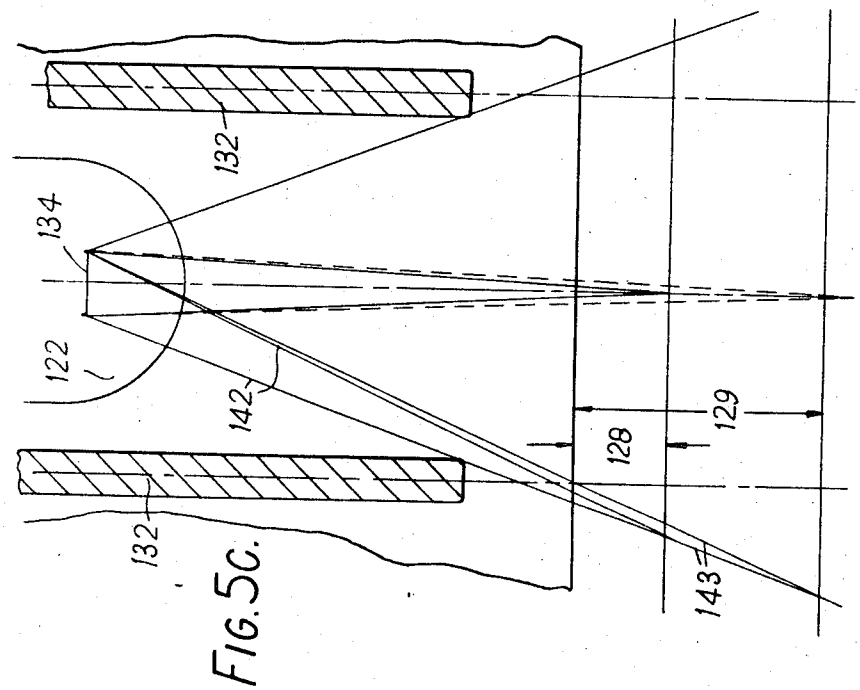


FIG. 5C.

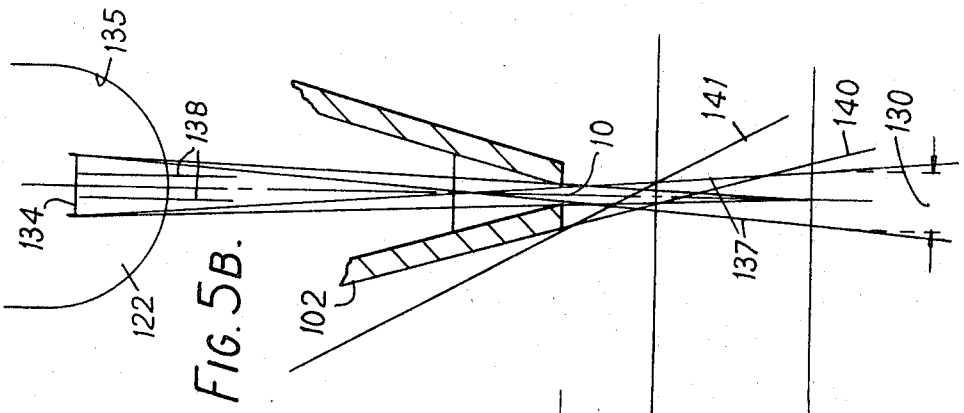


FIG. 5B.

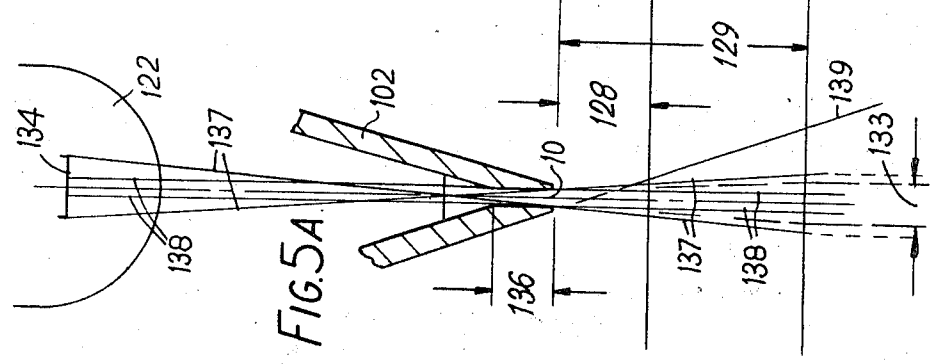


FIG. 5A

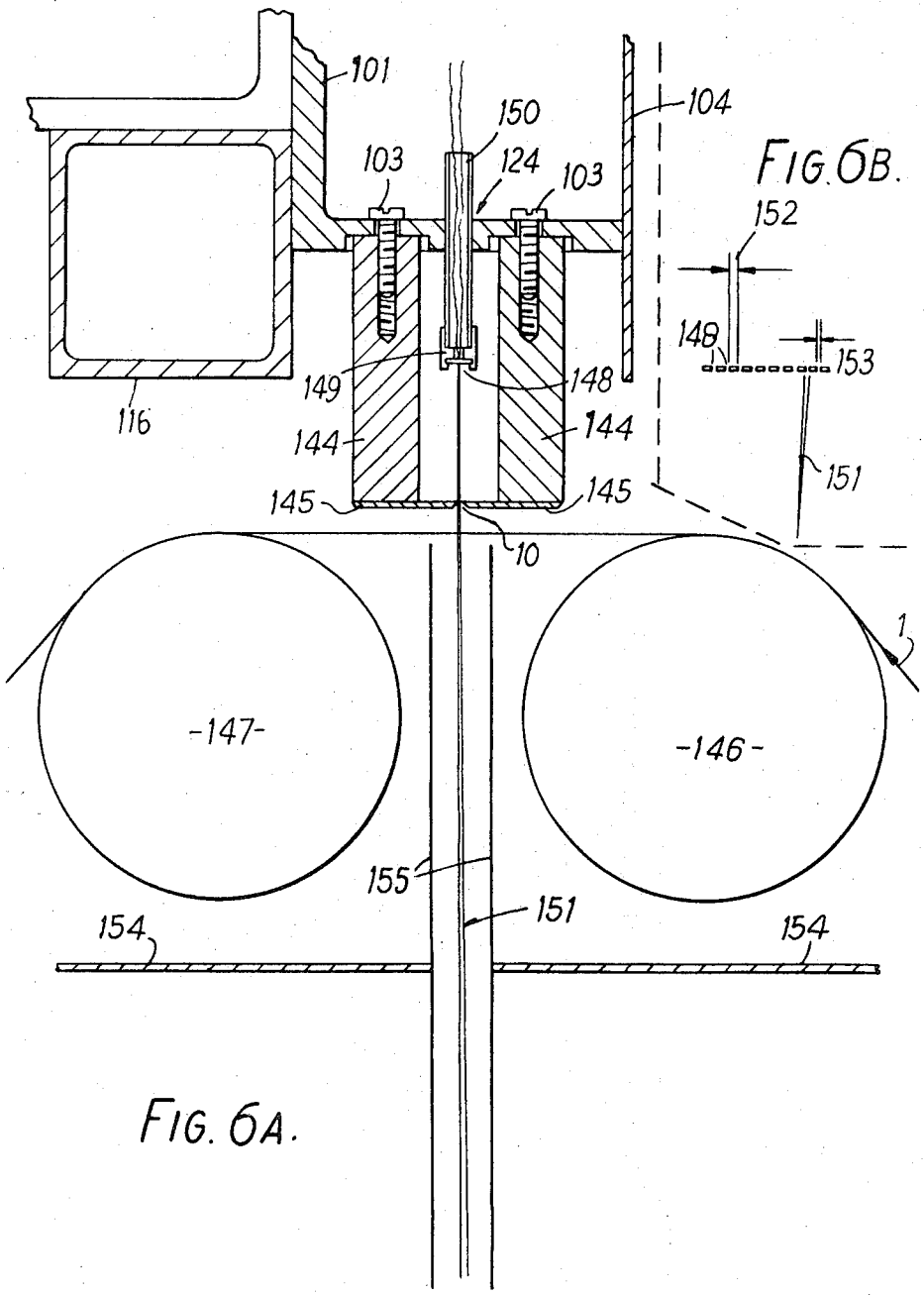

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-146-
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154

FIG. 6B.

FIG. 6A.

FIG. 7A.

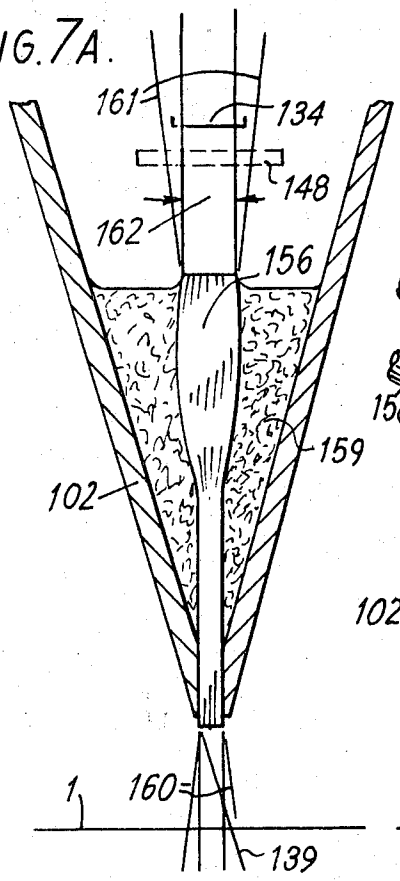


FIG. 7B.

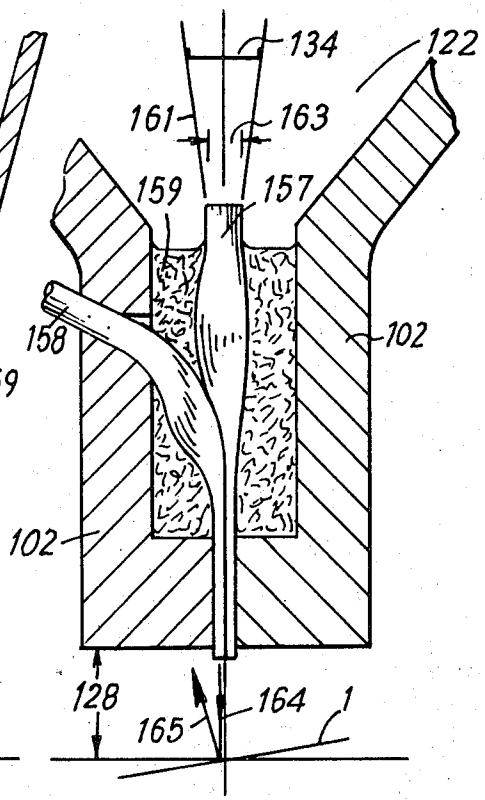


FIG. 8.

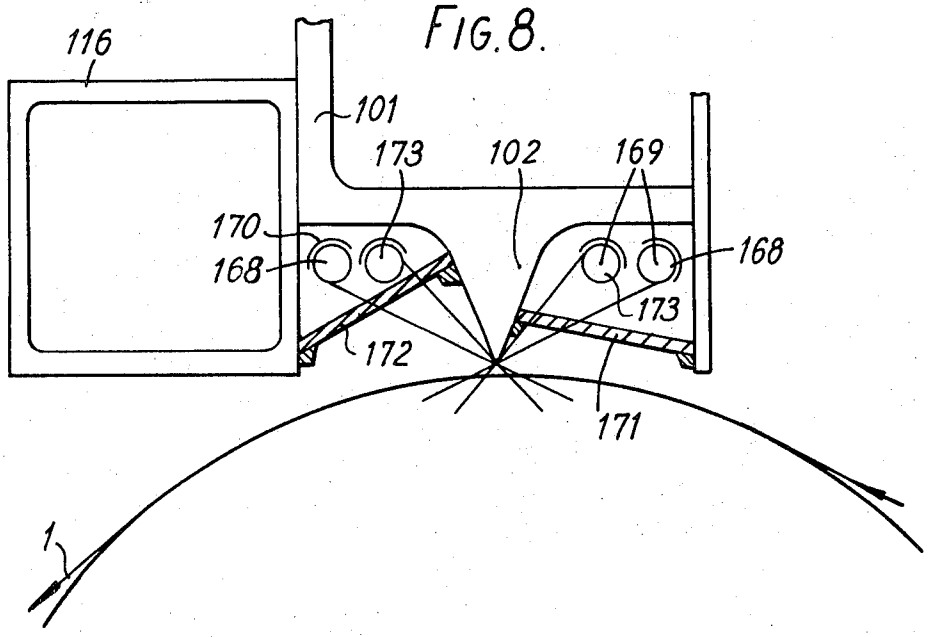


FIG. 7C.

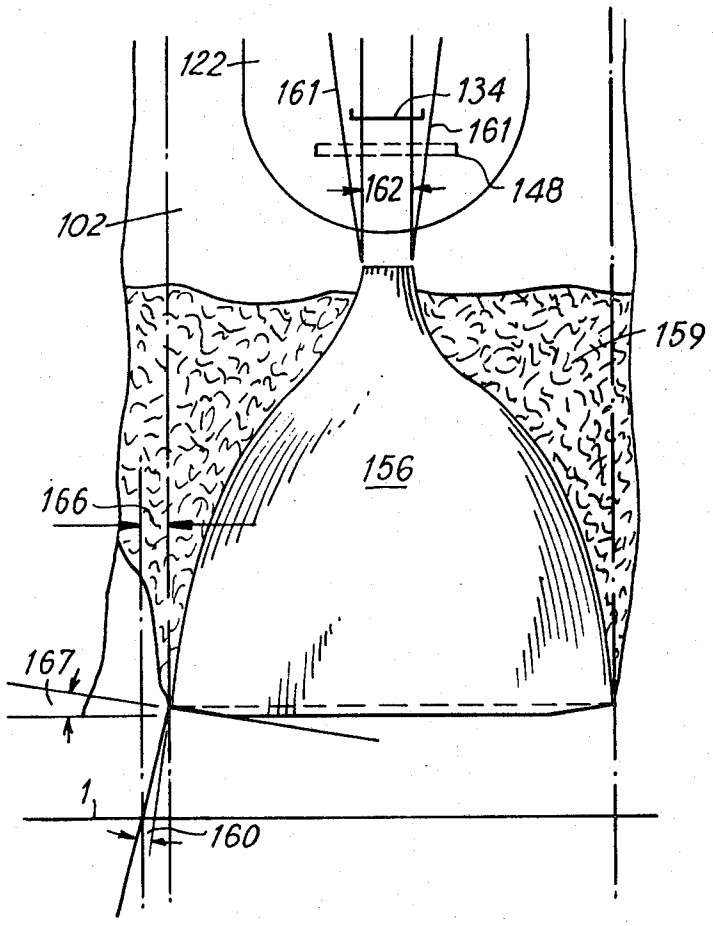


FIG. 7D.

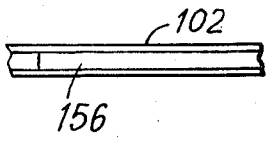


FIG. 7E.

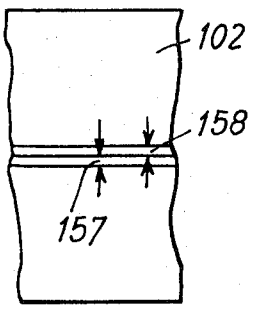


FIG. 9.

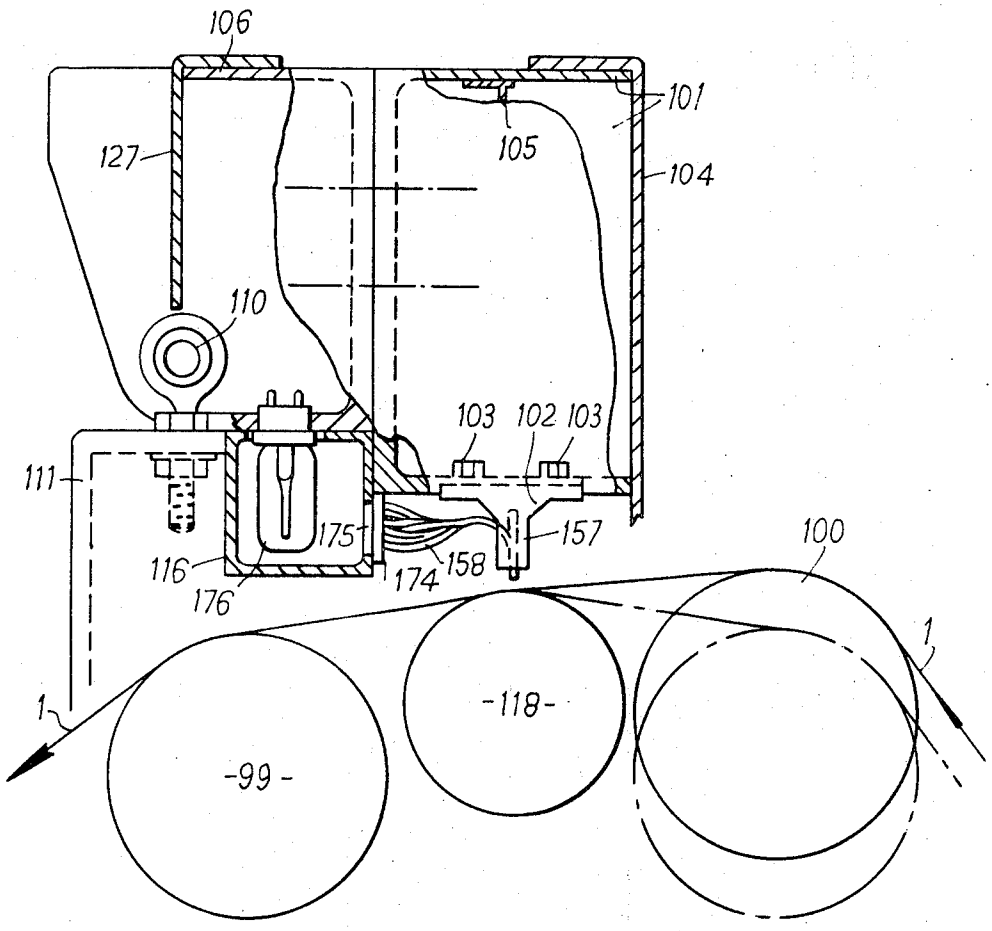

106
101
105
127
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175
157
100
116
158
174
176
1
1
-118-
-99-

FIG. 10A.

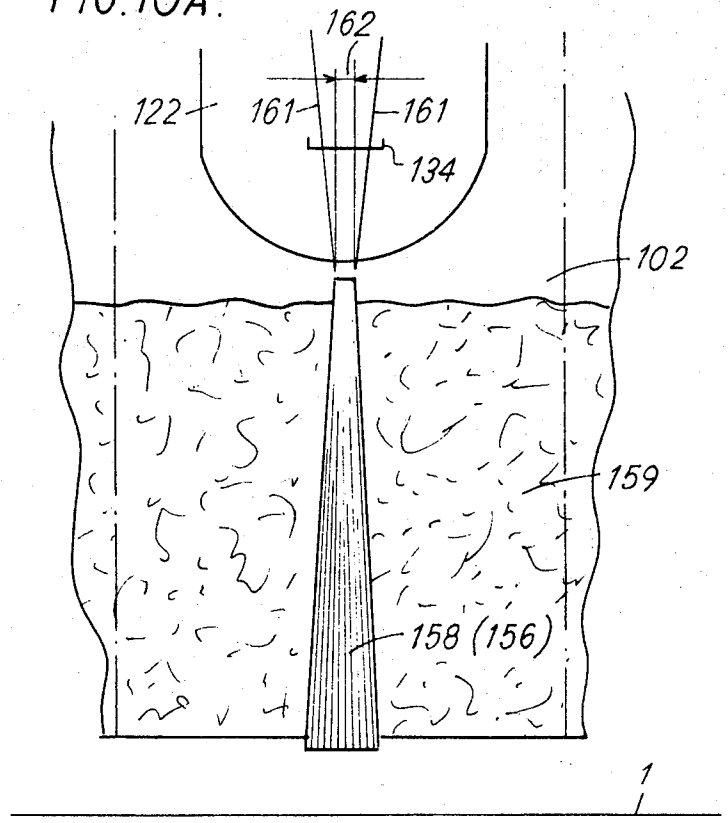
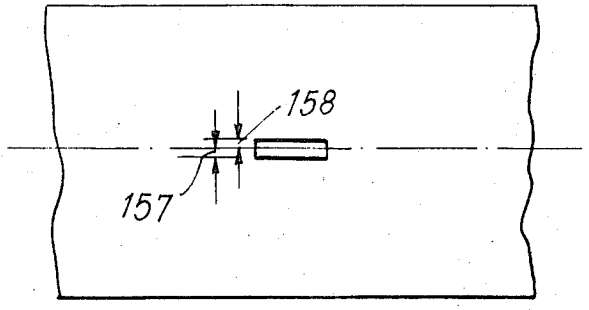


FIG. 10B.



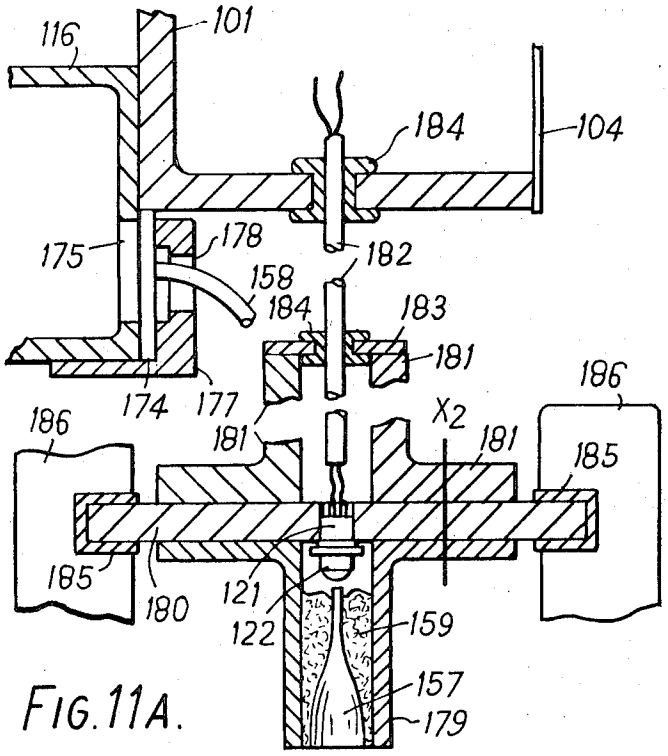
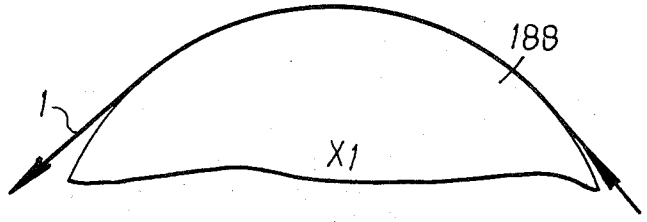


FIG. 11A.



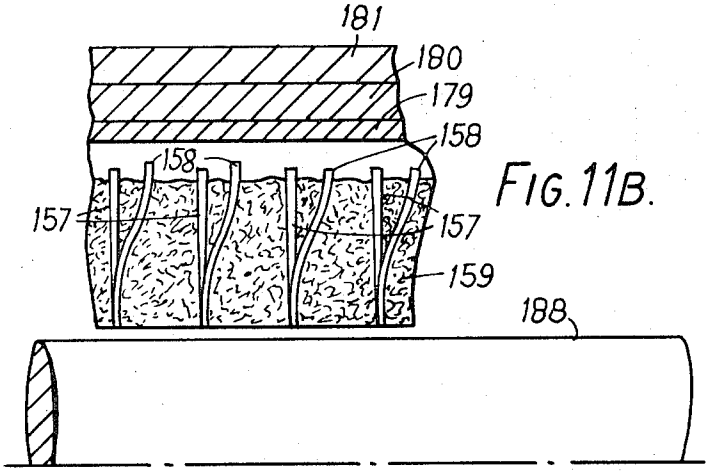


FIG. 11B.

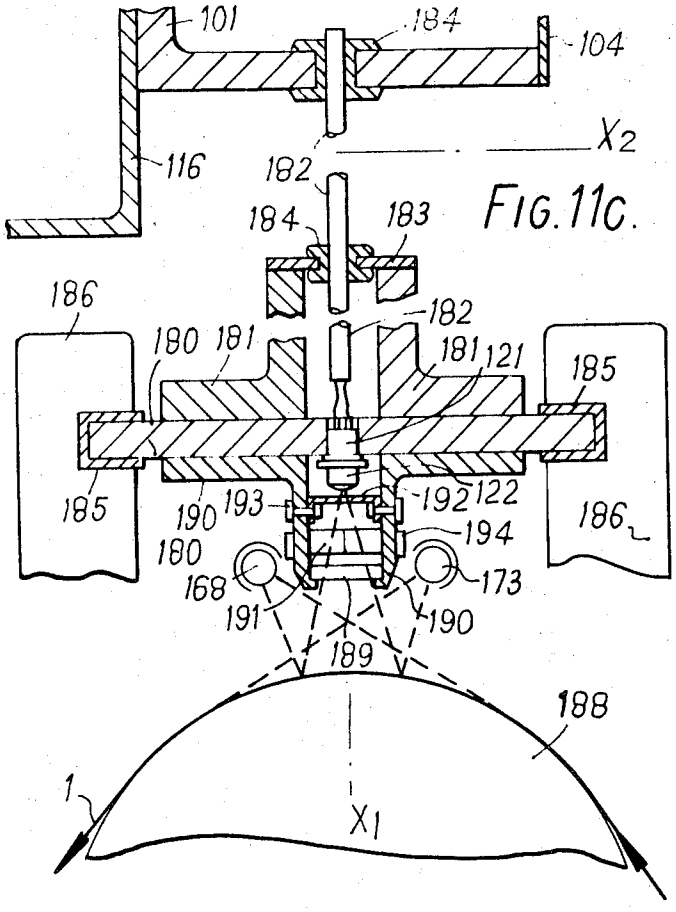


FIG. 11C.

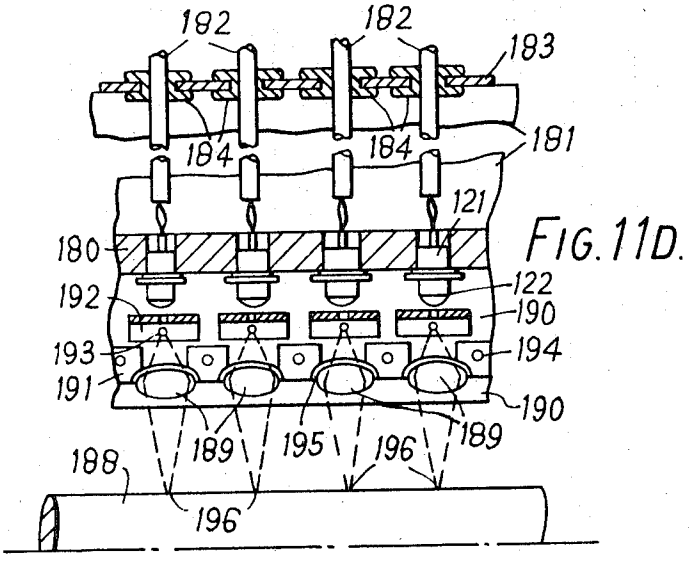


FIG. 11D.

FIG. 12A.

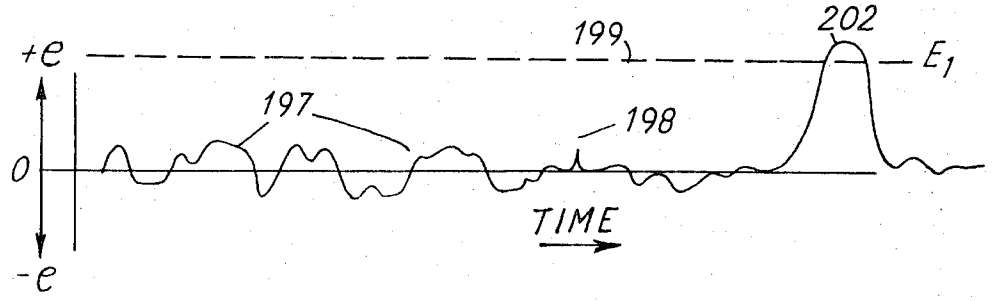


FIG. 12B.

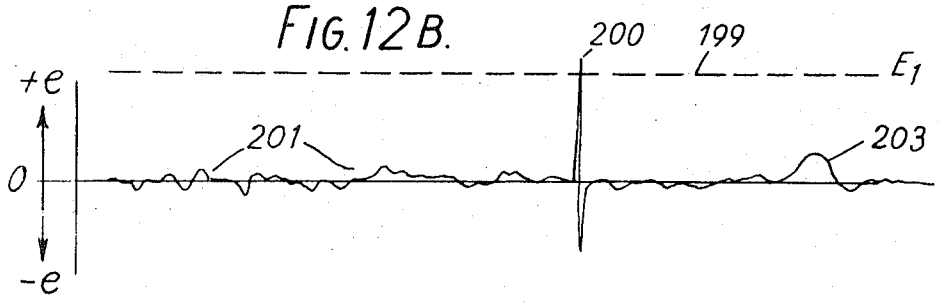
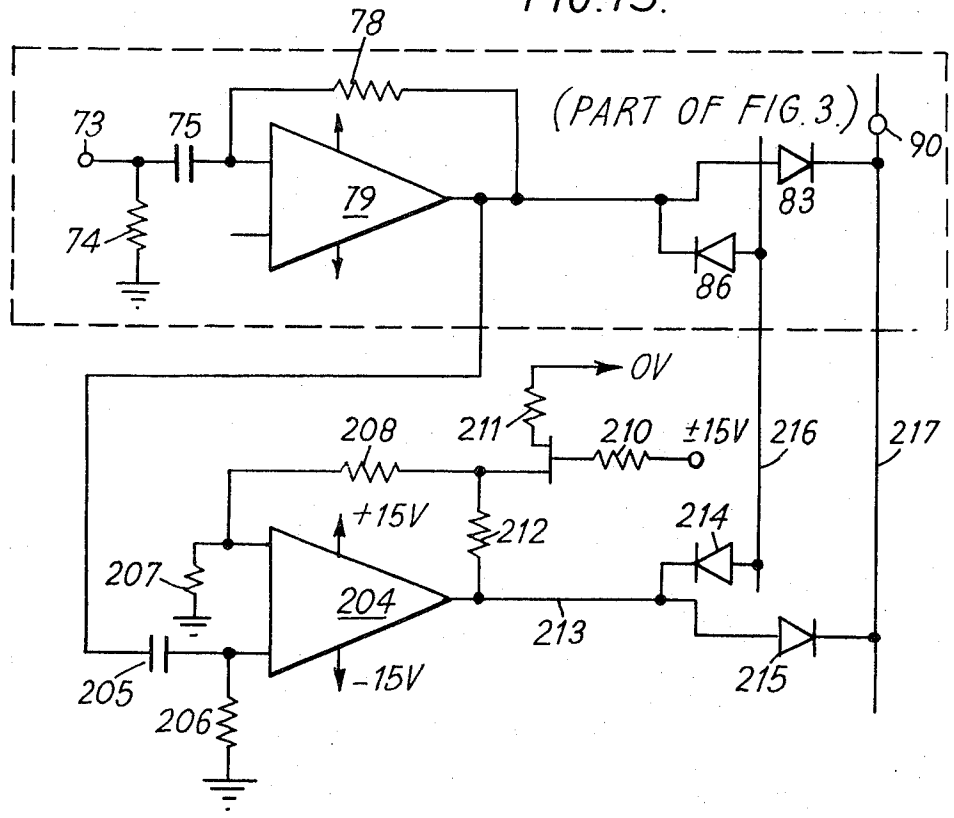


FIG. 13.



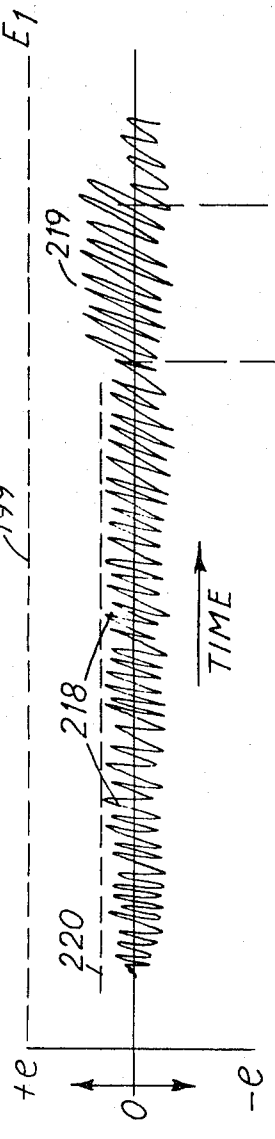


FIG. 14A.

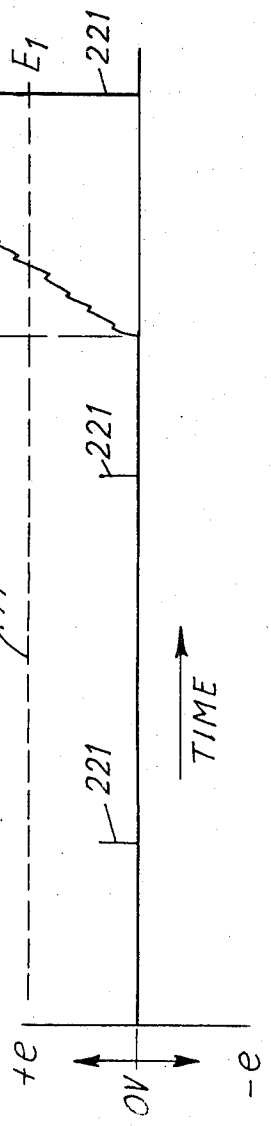


FIG. 14B.

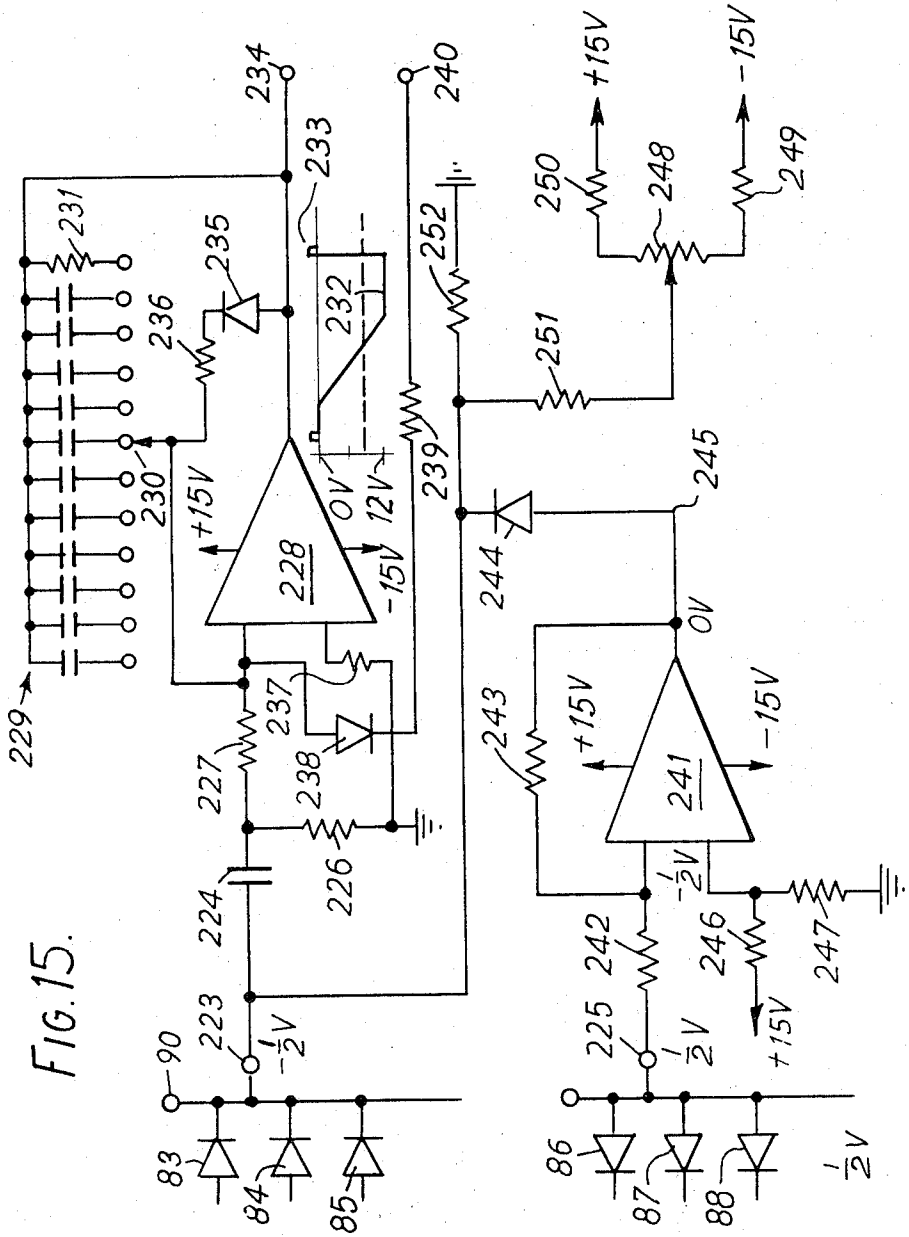

229
231
230
235
236
232
234
233
240
252
239
+15V
0V
12V
-15V
228
237
238
227
226
224
223
90
83
84
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251
-15V
86
87
88

FIG. 15.

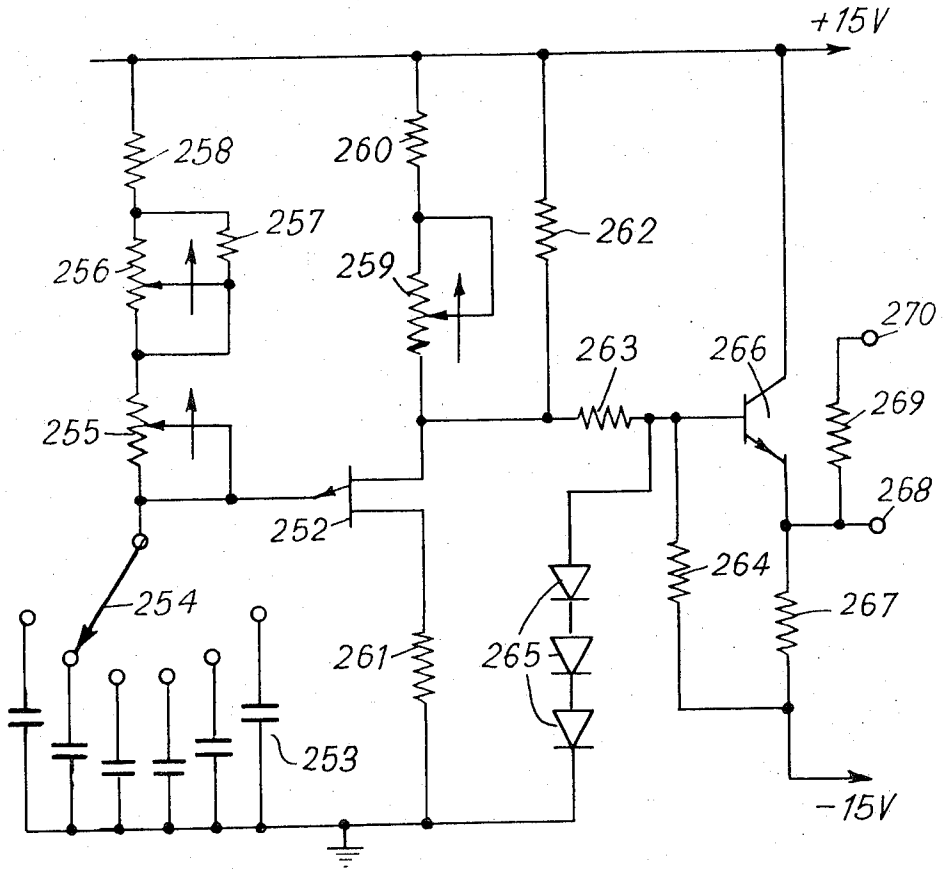
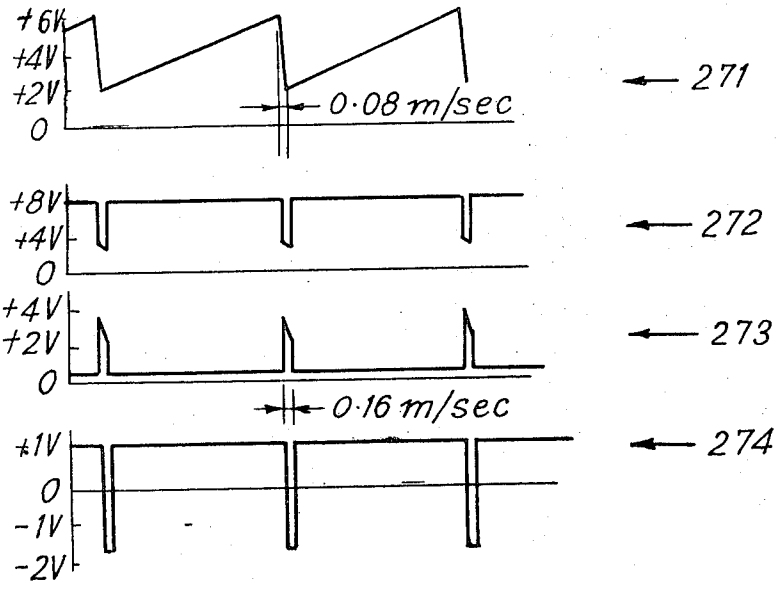

+15V
258
260
257
262
256
259
270
263
266
269
255
252
268
264
254
267
261
265
253
-15V

FIG. 16.


+6V
+4V
+2V
0
0·08 m/sec
271
+8V
+4V
0
272
+4V
+2V
0
273
0·16 m/sec
+1V
0
-1V
-2V
274

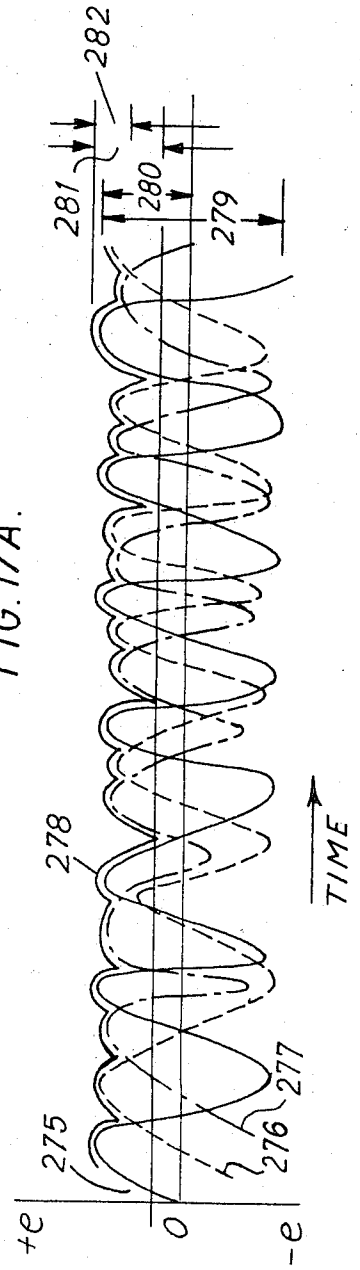


FIG. 17A.

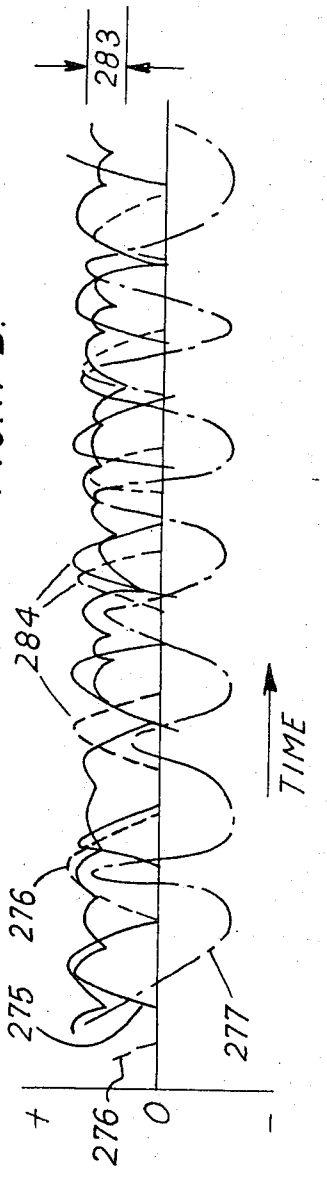


FIG. 17B.

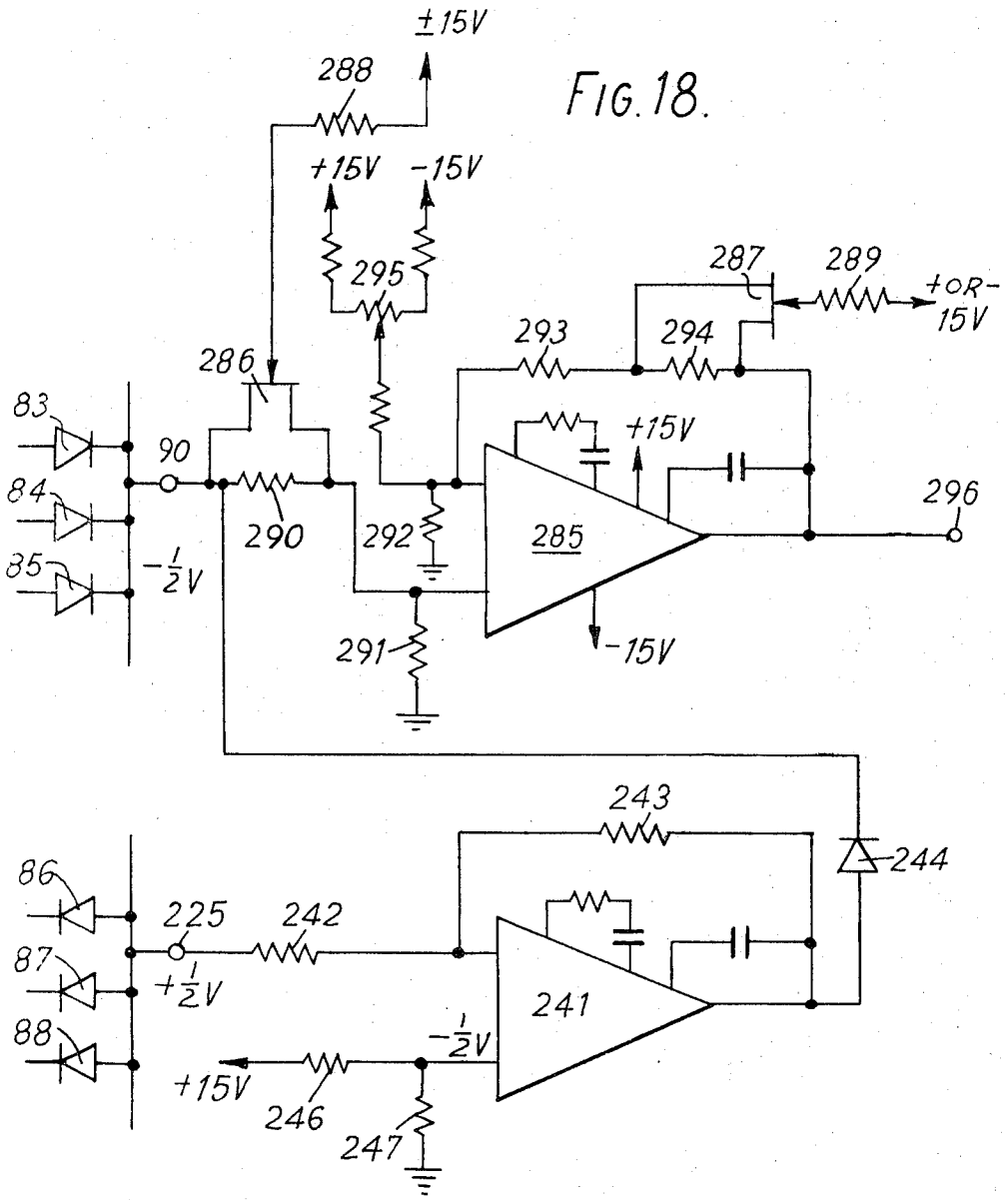

±15V
288
+15V
-15V
295
287
289
+OR-
15V
293
294
286
83
84
85
90
290
292
+15V
285
296
-15V
291
243
244
86
87
88
225
242
241
+15V
246
247

FIG. 18.

FIG. 19A.

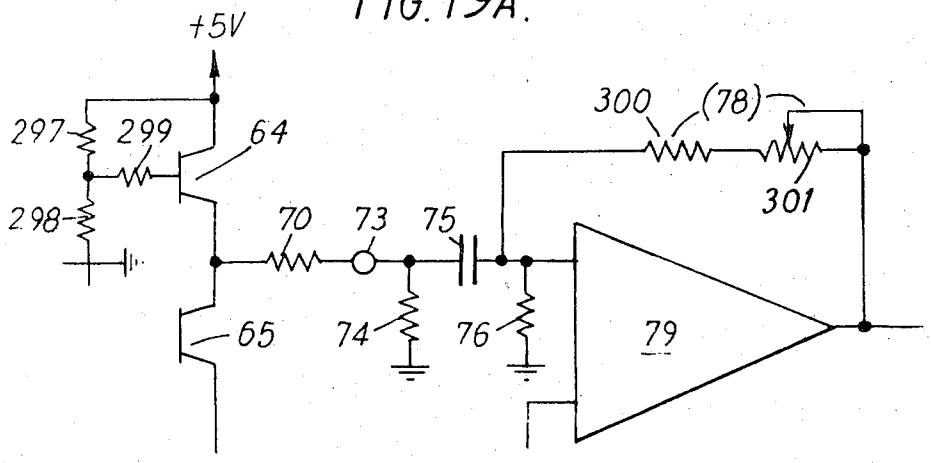
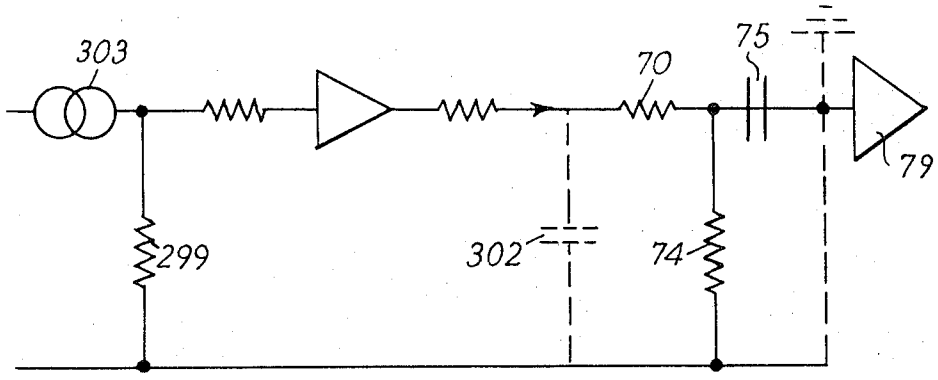


FIG. 19B.



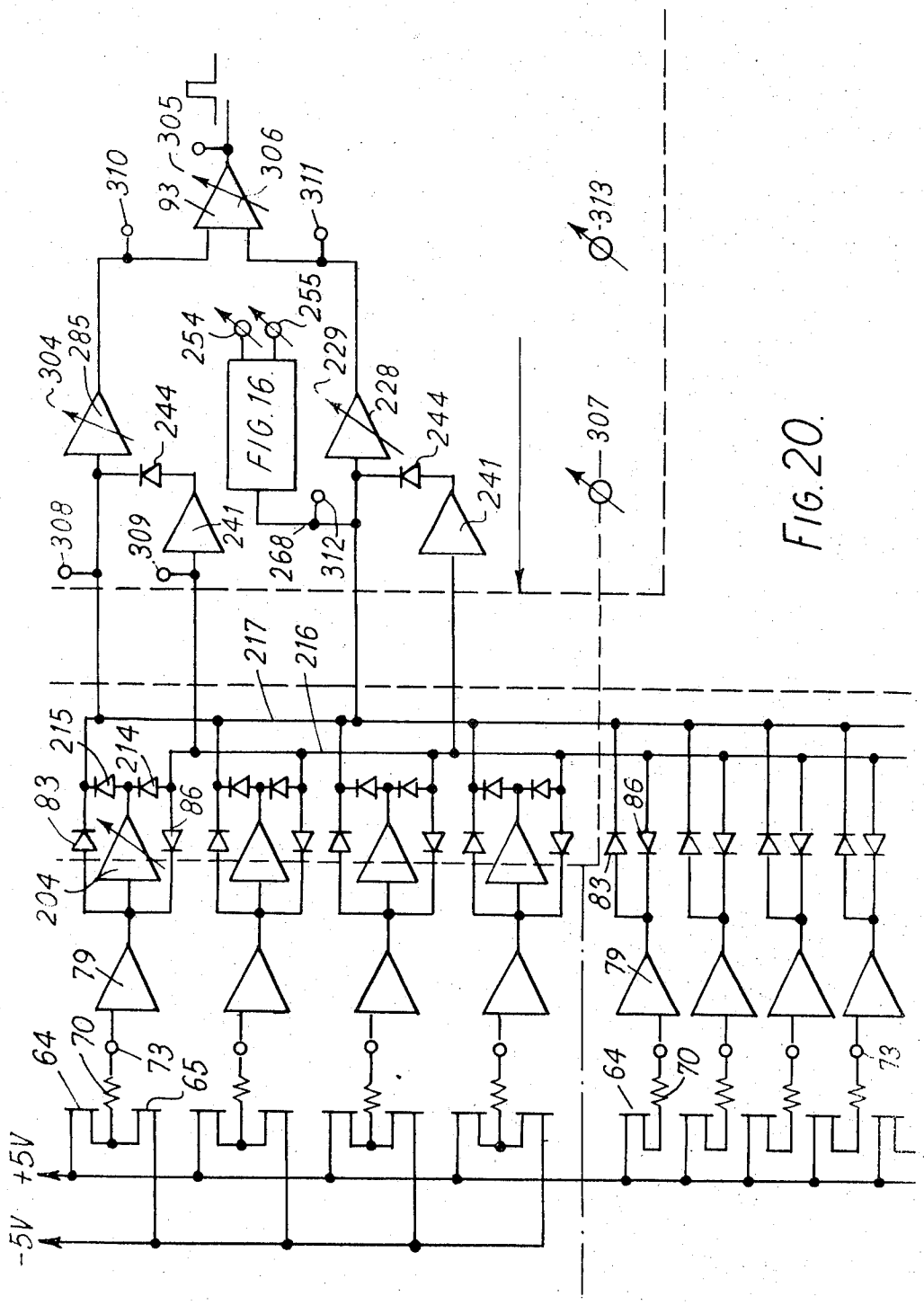

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FIG. 16.
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312
217
216
215
214
83
86
86
83
204
79
79
64
70
73
65
64
70
73
+5V
-5V

FIG. 20.

CIRCUITS FOR DERIVING A COMMON OUTPUT SIGNAL FROM A PLURALITY OF AMPLIFIERS IN APPARATUS FOR DETECTING BLEMISHES IN SHEET MATERIAL

This invention relates to circuits for deriving a common output signal from a plurality of amplifiers.

It is often desirable to combine the output signals from a plurality of amplifiers to produce a common output signal. For instance, in apparatus for detecting defects in sheet material arranged to flow past an inspection head of the apparatus, of the kind comprising light source means arranged to direct light onto the sheet material, a plurality of photosensitive devices arranged in the inspection head in a line transverse to the direction of flow of the sheet material so that the photo-sensitive devices receive light transmitted through or reflected from respective adjacent portions of the sheet material as it passes the photosensitive devices, each device being adapted to generate an electrical signal dependent on the intensity of light received by the device and electronic circuit means arranged to receive the electrical signals from the photo-sensitive devices and to sense variations in the intensity of light received by one or more of the devices due to defects in the sheet material, the electronic circuit means including a plurality of amplifiers each receiving the electrical signal generated by at least one of the photosensitive devices, it is desirable that the outputs of the amplifiers are combined to produce a common output signal which can then be supplied to further circuit means of various kinds operable to process as necessary the common output signal, thus obviating the necessity of providing separate further circuit means for each and every amplifier.

A problem which arises in combining the outputs of a plurality of amplifiers is that of ensuring that the random noise signals present in the output of each amplifier are not combined to produce a large resultant noise signal component in the common output signal, which would prevent the detection at the common output of any but comparatively large useful signals generated by one or more of the amplifiers.

According to this invention there is provided a circuit for deriving a common output signal from a plurality of amplifiers each adapted to generate in response to an input signal individual to the amplifier an electrical output signal including a random noise signal, the circuit comprising a plurality of rectifiers each having one terminal adapted to be connected to the output terminal of one of the amplifiers and its other terminal connected to a common output terminal, and means for biasing the rectifiers so that each of the rectifiers can be put, in operation, in a conducting state so that the random noise signals from the amplifiers are combined at the common output terminal to produce a resultant noise signal having an amplitude less than those of the individual noise signals.

Preferably, the circuit includes a first plurality of rectifiers connected to a first common output terminal and arranged so that, in use, the positive portions of the output signal of each amplifier are combined at the first output terminal, and a second plurality of rectifiers connected to a second common output terminal and arranged so that the negative portions of the output signal of each amplifier are combined at the second common output terminal.

Suitably, one of the common output terminals is connected through an inverter to the other common output terminal thereby in use to combine the signals appearing at the two common output terminals.

In one form of the invention, there is provided apparatus for detecting defects in sheet material of the kind set forth, and incorporating a circuit as defined above for deriving a common output signal from the plurality of amplifiers of the apparatus.

Suitably, the inspection head of the apparatus comprises a housing on which are mounted a plurality of photo-sensitive devices and a separately formed, replaceable collimating member having an aperture through which in operation light transmitted through or reflected from the sheet passes to fall onto the photosensitive devices, the collimating member being detachably fixed to the housing.

Preferably, the inspection head comprises a plurality of separate head sections each forming a housing as defined above, each head section being detachably mounted on a common support member extending transversely of the direction of flow of sheet material through the apparatus.

Advantageously, the support member is hinged to a main frame of the apparatus, to enable the inspection head to be moved from an operative position in which the aperture of each collimating member is close to the path of travel of sheet material.

Suitably, each housing is in the form of an airtight case, and means are provided for supplying dust-free air under pressure to the housing, the air leaving the housing through the apertures in the collimating members.

Advantageously, adjustment means are provided for adjusting the distance between the apertures of the collimating members and the path of travel of sheet material.

Suitably, the apparatus includes support means providing a support surface for supporting sheet material as it passes the inspection head, the support means being adjustable to enable the support surface to be made convex, flat or concave.

Each collimating member may comprise two side walls converging towards the path of the sheet material, the aperture being defined between flat faces formed at adjacent ends of the side walls and parallel to the plane of symmetry of the member, the member being divided by ribs extending between the side walls into sections each corresponding to one of the photo-sensitive devices. Alternatively, the adjacent ends of the side walls may be cut off in a plane parallel to the plane of movement of the sheet past the members, the aperture being defined by the adjacent edges of the inner surfaces of the side walls.

The invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a cross-sectional representation of the collimating optical system of a known inspection head using gas filled photocells.

FIG. 2 is the circuit diagram for defect signal processing associated with the inspection head of FIG. 1.

FIG. 3 is a circuit diagram for defect signal processing using as sensors phototransistors and solar cells.

FIGS. 4 (4A, B, C, D, C/D, E, F) define design details of an improved standard inspection machine with attachable variants of aperture casings.

FIGS. 5 (5A, B, C) show constructional details of the nose design of the most used aperture casing.

FIGS. 6 (6A, B) shows an aperture casing design particularly adapted for the use of transparent coated materials.

FIGS. 7 (7A, B, C, D, E) shows an aperture casing using fiber optics.

FIG. 8 shows the adaptation of the aperture casing of FIGS. 4 and 5 when used for inspection in the infra red region.

FIG. 9 shows a preferred method of illumination with the fiber optics type aperture casing of FIGS. 7B, C, and E.

FIGS. 10 (10A, B) shows an aperture casing using fiber optics for statistically sampling minute particles.

FIGS. 11 A and B shows an oscillating aperture casing using fiber optics for inspection fine line, scratches extended in the direction of web flow.

FIGS. 11C and D shows an alternative design to the aperture casing of FIGS. 11A and B using lenses.

FIGS. 12A and B are oscillograms showing differentiation of defect-signals.

FIG. 13 is a circuit diagram of a differentiating amplifier.

FIGS. 14A and B are oscillograms showing defect integration and noise elimination.

FIG. 15 is the circuit diagram of an integrator and invertor when processing the outputs of many amplifiers.

FIG. 16 is the circuit diagram of an integrator resetting pulse generator.

FIGS. 17A and B are oscillograms showing the zeroing of noise signals at the input of an amplifier or an integrator when such are processing the outputs of many amplifiers.

FIG. 18 is the circuit diagram of an inverter and variable gain amplifier used with zeroed noise input.

FIG. 19A is the circuit diagram of a biased phototransistor and of a coupling link between the phototransistor and one of the standard amplifiers.

FIG. 19B is the equivalent diagram of FIG. 19A.

FIG. 20 is the block circuit diagram of an inspection system using some of the elements shown in the previous Figures.

FIG. 1 is a crossectional representation of the essentials of an operational inspection system for sheet materials which exhibit some transparency using high vacuum type or gas filled photocells and collimating optics.

Sheet material 1 is passing over support members, such as rollers 2 and 3. It is illuminated by lamps 4, 5 and 6 with constant intensity. For example, lamps 4, 5 and 6 are fluorescent lamps supplied from a highly regulated DC source. The uniformity of illumination is not affected by reflections from rollers 2 and 3 because U-shaped member 7 shields the rays of lamp 6 and the inspected "line" of the sheet material. The uniformity and constancy of the illumination is also ensured by not blocking any light beams falling upon the inspect line from any of the lamp surfaces. FIG. 1 is a representation in full scale; hence it can be seen that the width of the inspected line 8 (to be referred to as the inspect-line) is of the order of one thirty-second of an inch.

Nose 9 of the inspection head contains apertures 10 and 11. These apertures are approximately 1 inch long in the direction at right angles to the flow of material. The length of the apertures in the cross-machine direction (at right angles to the flow of materials) are defined by members 12 which extend at approximately 1 inch intervals close to the very tip of the nose, terminating near aperture 10.

Light reflected and transmitted at the inspect-line 8 passes through both apertures 10 and 11 and falls upon the cathode 16 of photocell 13.

This arrangement forms a collimating optical system, because the distance 14 between apertures 10 and 11 is an order of magnitude greater than distance 15, that is the distance between aperture 10 and the inspected material. The width of the inspect-line in the direction of flow is approximately the same as the width of aperture 10. The optics of FIG. 1 defines the inspect-line as approximately one thirty-second of an inch.

The essential parts of the system are the aperture or slits 10 and 11 and the photocathode 16. Any change of the reflected or transmitted light due to a defect changes the photocurrent through photocathode 16 and after suitable amplification is sensed as a defect.

Aperture 11 consists of a fixed member 17 and an adjustable member 18. By adjusting member 18, the amount of light falling upon photocathode 16 can be regulated and made uniform in many photocells. Such adjustment of aperture 11 hardly affects the width of the inspect-line 8.

The electronic circuit associated with the sensing or (using other words) inspection head 19 is shown in FIG. 2.

Eight photocells, 20 to 27, each viewing through their 1×0.020 inch windows the corresponding section of the inspected material which sections have an area of approximately $1 \times 1/32$ inch. Thus FIG. 2 shows a unit of an inspection head, 8 inches in the cross machine direction. In practice, a number of such head units form a head system. For example, 20 such head units would be required to fully inspect a 160 inch wide sheet.

Only essentials of the circuit connected to photocells 20, 22 are shown. For clarity and to avoid repetition, the circuits processing the output of cell-pairs 21–23, 24–26, and 25–27 are identical and are not shown. Also, only essentials of one-half of the differential amplifier 51 is given, again for clarity. The circuit of the other half is identical.

The photocell currents develop voltage signals like 42, across their load resistor 28, 29 which appear unchanged at the outputs 34, 35 of source followers 30, 31 (or at inputs 44, 45 of amplifier 51). The head outputs generated by photocells 21, 23, 24, 25, 26, and 27 are led to terminals 36, 37, 38, 39, 40 and 41 via six additional source followers with identical circuitry, not shown.

Input signal 42 is amplified linearly to signals 60 and 61. Signal 61 is the mirror image of signal 60. The A.C. gain is set by switch type potential divider 50 in six steps, altering the feedback voltage level led to feedback resistor 49. The lowest A.C. gain is approximately 10, defined by resistors 49 and 44. Potential divider 50 multiplies this gain in six steps to 50, 250, 450, 750, 1,250 and 2,000.

The amplifier output signals 60 and 61 present at leads 52, 53 are fed via diode gates 54, 55 to a Schmitt trigger type generator 62 which feeds output pulse 63 to one or more readout units, such as counters, warning light, sound alarms, recorders, process control com-

puter logics, etc. Gating diodes **56, 57** belong to cells **21, 23,** their signals amplified through identical circuits.

The **18** cell head unit feeds in pairs four identical amplifying systems. Altogether eight gating diodes (only four shown) are joined at their cathodes; at this joint, the gate level is set via potential divider **59** connected via buffer resistor **58.** Hence, in addition to the six step gain switch, the sensitivity of the system can be adjusted by the lowering or raising of the gate level.

The circuit design is governed by the following requirements:

a. Uniformity of response.

As each cell, or pair of cells, or a selected number of parallel cells, are connected to one of many amplifiers, each such system has to have the same response and amplification to define an inspection sensitivity level which is uniform for the whole system. As the cells are set to uniform response by the adjustable aperture members **17** and **18,** each amplifier has the same amplification and response and exhibit long term stability.

This is accomplished by using identical values for corresponding resistors and by defining the gain of amplifier **51,** having an open-loop gain of over 50,000 by negative feedback and ratios of resistors.

b. The defect signal to noise (signal generated by unblemished sheet) ratios of a limiting defect to be at least 3 to 1, and the defect signal amplitude is to be raised to a level of several volts for ease of readout.

The amount of light falling on photo-cathode **16** defines the current available for amplification.

As the human eye can only differentiate a contrast of 1 to 1½ percent according to observers, the faintest change of a uniform sheet surface which the eye may judge as defective can be regarded as being of the same order of magnitude, that is, approximately 1 percent. In practice, it is seldom possible to count upon the reliable detection of a percentage change of the light smaller than 2 percent, because the texture of the unblemished material is seldom completely uniform and generates "noise," i.e., a signal level which must be kept below the readout gate level. It is indeed a very faint or minute defect which will produce 2 percent modulation. The equivalent (in cell modulation) smallest full black spot generating 2 percent modulation when two 1 × 1/32 inch sheet material sections are observed differentially is approximately one thirty-second inch in diameter.

It was found that the average current in a high vacuum or gas type photocell is 0.2 microamperes when the light is reflected from a matte white surface in the system represented by FIG. **1.**

In order to raise 2 percent modulation of this current above a readout gate level of 8 volts, the photocell load resistors **28, 29** were made 2.2 megohms and the so generated voltage (8 to 10 millivolts) is amplified by the voltage amplifier 1,000 times in the differential amplifier **51.** In order to reach the very limit of the human observer, the highest voltage gain of amplifier **51** is 2,000 corresponding to a detection sensitivity of one percent modulation.

c. The system noise should be kept to an order of magnitude below the useful signal levels. It was found that without light, the peak-to-peak noise level at the output of the amplifier was of the order of 0.3 volts. When light was reflected from a white sheet, the peak-to-peak noise was of the order of 1 volt. Both measured at the maximum amplification of 2,000.

d. The system to be free of interference.

For this reason, the inspection head is electrostatically shielded by its metal case.

The inspection head system is separated from the control cabinet by cable **43.** This cable can reach 100 to 200 ft. lengths. Near certain machines, e.g. near fast paper machines, the noise and associated inconvenience close to the machine is such that it is only practical to operate or check-out the control system for the inspection head in a separate room. Hence, it is essential that interference signal pick-up, always present in an industrial establishment, is kept below a few millivolts. This can be done by converting the high value of the photocell resistors **28, 29** (2.2 megohms) into a low output impedance so that capacitive interference and pick-up is substantially eliminated.

In FIG. **2** the impedance conversion is performed by field effect type source followers **30, 31.** The output impedance of the output leads **34, 35, 36** to **41,** is of the order of 100 ohms only. The value of the load resistors **32, 33** is much reduced by the current gain of the source followers.

e. Immunity to "in-phase" disturbances.

It is well known in the art that a differential system has many advantages by being immune to in-phase interference signals. Feeding cells **20** and **22** to the inputs **44, 45** of differential amplifier **51** via source followers **30, 31,** that is to each half of two completely symmetrical circuit configurations (of which only one-half is shown in details of essentials) has the said merits. Without the differential system, in-phase interference signals would be detected from eccentricity of rollers, changes in environmental illumination, some changes generated by the flutter of the sheet material, variations in power supplies both due to insufficient regulation or power line frequency hum.

f. Limited D.C. gain in system.

The inspection system must not be affected when cells are blocked (covered) at edges of the inspection machine.

When a differential pair, say photocells **20, 22,** (or **21** and **23,** or **24** and **26,** or **25** and **27**) is exposed to such in-phase disturbances (say both cells are covered) the corresponding level changes at the input of amplifier **51** are identical in amplitude and phase and hence are not observeable at the output **52, 53.** However, in practice it is hardly possible that near the edge of the inspection system or due to some failure of one or many cells or due to misalignment in the balance of a pair of cells, this condition can be maintained for long periods. Hence, the amplification of "D.C. level changes" of this type have to be limited such that it cannot reach the readout gate level of, say, 8 volts. In FIG. **2,** this is done by the feedback link consisting of resistors **46, 74** and capacitor **48.** The A.C. feedback affecting amplification of useful frequencies, say above 2 cycles, is decoupled and eliminated by capacitor **48.** However, the D.C. gain of amplifier **51** is limited to 2 by the ratio of the value of resistors **46** plus **47** over that of resistor **44.** 200,000 ohms over 100,000

ohms equals 2. The stated 0.2 microampere photocell current results in a 0.44 volt D.C. level across cell loads **28, 29** and amplifier inputs **34, 35.** This input voltage multiplied by 2 can only result in a D.C. level change at outputs **52** or **53** of less than 1 volt. As the readout level is above the gate voltage of 8 volts, the clean readout of the system is not affected materially by the lack of balance of the differential pairs in the inspection head.

g. The D.C. levels of the outputs of the amplifiers should be identical and preferably be at ground level.

The source followers **30, 31** can be replaced by operational amplifiers with a gain of **1.** Then the output levels can be made within a few millivolts to be at ground level when the cell currents are low. The very limited D.C. gain of the amplifier **51** ensures that the D.C. output level at leads **52, 53** is substantially the same as the near ground level of the inputs at **44, 45.**

Because the outputs of the amplifiers are at the same D.C. level (near ground), gating diodes **54, 55, 56, 57** and so on result in complete separation of the outputs of the differential amplifiers, and by combining in this manner the outputs of several amplifiers, the combined noise level is the same as in each amplifier.

h. A defect has to be detected when it is lighter or darker than the mean intensity of the inspected material.

In the differential amplifier **51** a signal fed to one of the inputs appears at the outputs **52, 53** in opposite phase and equal in amplitude, hence at one of the outputs any signal has a positive polarity and actuates the Schmitt trigger pulse generator through one of the diodes **54, 55, 56, 57.** A defect signal which is more positive than the outputs of other amplifiers effectively blocks the gating diodes of such amplifiers.

The defect signal defined in typical signal pattern **42** is between time *t*1 and *t*2 and appears as a negative signal at output **53** and does not pass through the gating diodes. This signal at output **52** is a positive signal. Part of this signal above the gate level will then generate a Schmitt trigger pulse within the time interval *t*3, *t*2 as shown in pattern **61** and **63.**

i. The frequency response of the system must be high enough not to degenerate the fastest signal change due to a limiting defect travelling across the aperture **10** at the highest web speed. For example, when the sheet velocity is 2,000 feet per minute, i.e. $V = 400$ inches per second, a sharp edge parallel to the aperture with width D of 0.040 inch, passes the aperture in D/V seconds, i.e., 0.040/400 = 1/**10,000** second = 100 microseconds. Hence the rise and fall time of the electronic system should be 50 microseconds or better measured between ground and the gate level.

The essential features (*a*) to (*i*) of the inspection system described with the aid of FIGS. **1** and **2** are substantially improved in the embodiments of the invention which will now be described, by the use of up-to-date technology, such as silicon semiconductors, micro-circuits, operational amplifiers, i.e., up-to-date space age electronics.

Said improvements are disclosed under captions repeatedly lettered (*a*) to (*i*), in conjunction with FIG. **3,** which presents the essentials of the light sensors **64, 65, 68** and **69,** the circuit associated with the operational amplifier **79** plus the circuit of the readout unit formed by operational sensing amplifier (differential comparator) **93.**

Also the optical design can be improved and made such that it has universal application for all types of inspection requirements which much varies according to the material and its speed and the type of defectiveness. The universally efficient optical design of FIG. **4** of an inspection head has to process efficiently paper, nonwoven fibers, transparent and opaque plastics, film, photo-sensitive film and paper, X-ray film, magnetic tape, textiles, metals, etc.

In FIG. **3** for the photosensors, two alternatives are shown: phototransistors **64, 65** and solar cells **68** and **69.** Either pair can be connected to terminal **73.**

For phototransistors **64, 65** the base connection is not shown and only very limited advantage, if any, can be gained by using the base of the phototransistors in a feedback circuit, being part of the feedback loop of the amplifier, or by connecting the base to a DC potential by a suitable resistor thus defining the base current and the collector current of the phototransistor. By biasing the base of a phototransistor, the increased base and collector current is always associated with more noise simultaneously improving the response of the phototransistor. However, using a steady level of light represented by arrows **66** and **67,** the same condition can be obtained, namely setting the base current and the associated collector current to optimal values. As in most applications, associated with the surface inspection of bright sheet materials, a steady amount of light falls upon the sensing cells, this is the preferable way of influencing the response of the phototransistors.

The alternative sensors, solar cells **68, 69,** can only be used as diodes as shown.

The balance of the circuit is governed by the factors discussed under requirements (*a*) to (*i*) and, last but not least, the basic difference between a symmetrical differential amplifier (as shown by amplifier **51** in FIG. **2**) and an operation amplifier (as shown by amplifier **79** in FIG. **3**).

A symmetrical differential amplifier has two outputs and two inputs.

The operational amplifier, while internally substantially identical to a differential amplifier, has only one output. Hence, only one negative-feedback loop can be used, hence the input circuits cannot be symmetrical, and hence the differential sensing has to be accomplished preferably at one input of the amplifier.

Having only one output available in amplifier **79,** two sets of diodes have to combine the outputs of several amplifiers. One set of diodes **83, 84, 85** and so on, combining the signals with a positive polarity and diodes **86, 87, 88** and so on, combining the outputs with a negative polarity.

Hence, conveniently two output pulse generators are best used for readout, one dealing with the positive and the other dealing with the negative output signals. In FIG. **3,** only the output generator **93,** fed by positive pulses, is shown.

Describing the circuit of FIG. **3** in all its detail:

Photosensors **64,65** are connected via resistor **70** to the inverting input of operation amplifier **79** through capacitor **75.**

The D.C. gain of amplifier **79** is defined by the resistance ratio of resistor **78** over resistor **76.** The D.C. gain is **10.** As the input offset voltage is usually of the

order of 1 millivolt or less and as the input offset current is usually less than one-tenth of a microampere, the resulting differential voltage between the inputs of the operational amplifier, when resistors **76** and **77** have values of approximately 100,00 ohms, is less than a few millivolts. Hence, if this differential voltage is amplified only by a factor of 10, the potential of the output of the differential amplifier is within **10** millivolts at ground level as long as resistors **76** and **77** are connected to ground. This is quite an important feature of the circuit of FIG. **3** because then a large number of operational amplifiers, like **79,** can be combined by diodes, like **83, 84** and **85,** and the useful output signals can be in the range of **50** millivolts or higher. In order to obtain the least differential input voltage due to resistors **76** and **77,** the value of resistor **77** is made to be equal to the value of resistor **76** paralleled by resistor **78.**

When the photosensors, that is resistor **70** or resistors **71** and **72,** are connected to the input terminal of amplitier **79** via capacitor **75,** the A.C. voltage gain is defined by the resistance ratio of resistor **78** over resistor **74.** In FIG. **3,** this A.C. gain is 100 for frequencies at which capacitor **75** present a low impedance relative to the resistance of resistor **74.**

The low frequency limitation or the time constant of the amplifier is defined by resistor **74** and capacitor **75.** Due to the negative feedback at the inverter input, this input is at virtually ground level, hence the time constant is defined by the capacitance of capacitor **75** being paralleled by resistor **74.** Practical values for time constants vary from one millisecond to **1.8** seconds; the corresponding value of the capacitor **75** would be 0.1 microfarad and 180 microfarad.

Resistor **80** and capacitors **81** and **82** are used for frequency compensation and for obtaining stable operation in operational amplifiers which are capable of a fast response, such as Twin operational amplifiers Type 1437 in which there are two identical amplifiers of the type 1709. When the response can be reduced at lower web speed, operational amplifiers without external frequency compensation can be used such as the Twin amplifier Type ML747, housing two identical amplifiers Type 1741.

It was found that (without the influence of the photosensors) the operation amplifiers of the Type 1709 can have an adjusted rise time and fall time varying between 5 microseconds and 20 microseconds by selecting for the capacitance of capacitor **81,** 100 picofarads to 1,000 picofarads.

When the photosensors **64, 65** or **68, 69** are connected to terminal **73,** it is important to make the connections via resistor **70** or resistors **71, 72.** When the sensors are connected direct to terminal **73,** the effective input is at a virtual ground potential; hence the voltage gain is quite high, much above 100, described herein before. The result is ringing. There are best values for resistors **70, 71** and **72** to obtain optimal combined response of the cells and amplifier.

The circuit of FIG. **3** is best understood by regarding it as a current amplifier: as the inverted input is virtually at ground potential when the feedback resistor **78** has a value of 1 megohm, the sensitivity of the system is 1 volt at the output for 1 microampere photosensor input.

It was found that the input impedance at terminal **73** was of the order of 1,000 ohms using the values shown in FIG. **3.** Hence, making the value of resistor **70** or the values of resistors **71, 72,** 1,000 ohms will not materially affect the amplification of the system, but it will slightly affect the rise time and eliminate ringing.

For example, the effect of resistor **70** upon the rise time of the combined system and upon ringing, when the amplifier **79** proper is set to a response of 10 microseconds per volt, is as follows:

The phototransistors are the type FPT-100.

The range of the rise times measured is a function of the sensitivity of the phototransistor. Greater sensitivity results in slower rise.

Resistor 70	Rise Time	Notes
120 ohms	24 – 50 microseconds per volt	Both values for resistor 70, 120 and 470 ohms, exhibit some ringing. The ringing lessens as the value increases.
470 ohms	25 – 60 microseconds per volt	
1,00 ohms	40 to 120 microseconds per volt.	No ringing whatsoever.
Using solar cells 68, 69 of the C-51 type:		
Resistor 71 (or 72)	Rise time	Notes
250 ohms	10 microseconds	Some ringing.
500 ohms	10 microseconds	Very limited
1,000 ohms	30 microseconds per volt	No ringing.

Gating diodes **83, 84** and **85** are made to conduct by connecting the junction of these diodes to resistors **89** and **91.** As the output of the operational amplifier **79** is substantially at ground level due to the diode drop, the cathodes of diodes **83, 84, 85** and so on are at a − 0.6 volt level. This means that the signals on amplifier **79** and a large number of other identical amplifiers are all available at terminal **90.** When such a system is checked out, consisting of hundreds of photocells associated with a corresponding large number of amplifiers, it is essential that a sample method should be available to measure the system sensitivity of each cell with their associated amplifier at one terminal. It is possible to do this at terminal **90** by making all diodes slightly conductive. The output pulse **97** of the system, generated by differential sensing amplifier **93,** has a pulse amplitude which is limited only by the negative and positive saturation levels of an operational amplifier with large open loop gain. The gate level is defined by feeding a positive potential from 0 to say +12 volts, conveniently in half-volt steps to resistor **96** connected to one of the inputs of amplifier **93.**

The other input to amplifier **93** is connected to terminal **90** via resistor **92.** When the outputs of the amplifiers, **79,** etc., are at ground and the gating voltage at resistor **96** has some potential, say 1 volt, then the output of amplifier **93** is flipped in one saturated mode. If at any instant the potential at terminal **90** reaches + 1 volt, the differential sensing amplifier **93** is ready to flop over into the other saturated mode. If the saturated output level of amplifier **93** was negative, it would flip positive and vice-versa. It should be noted that in order to achieve conduction of gating diodes **83, 84,** etc., the

current flowing through the chain consisting of resistor **92,** diodes **94, 95** and resistor **96** (all in series) must be less than the current flowing into the diodes **83, 84,** etc., through resistor **91.** This is the case in FIG. **3** when the maximum gating bias level of + 12 volts are connected from a low impedance source to resistor **96.** The current through said chain is just under 1 milliampere, while the current through resistor **91** is approximately 1.5 milliamperes. Hence one-half milliampere is distributed evenly along gating diodes **83, 84, 85,** etc. The value of resistor **91** has to be matched to the number of gating diodes which are parallel. For example, 10,000 ohms value in resistor **91** will allow 10 microamperes each through 50 diodes.

Diodes **94, 95** limit the differential voltage excursion of the inputs of the amplifier **93** to 0.6 volts. Similar protection is required for most types of operational amplifiers.

Diodes **86, 87, 88** and so on pass a negative polarity to an identical circuit, but the resistor corresponding to resistor **91** would be fed from a +15 volt source and the resistor corresponding to resistor **96** would be fed from a negative low impedance gating biasing source. The two gating bias sources being always equal, but of opposite polarity.

In order to obtain from differential comparators, sensing positive and negative signals, output pulses of the same polarity, the connections to their inputs simply have to be reversed.

The positive and negative common output signals can be combined at a single output terminal, by inverting one of the signals using a suitable inverter as described below, and supplying the inverted signal and the other non-inverted signal, to the single output terminal.

The noise signal reduction at the output terminal **90** is shown by FIGS. **17A** and **17B.** Three noise signals **275, 276** and **277** combine to resultant **278,** the peak-to-peak amplitude of which **281,** is much smaller than amplitude **279** or the rectified amplitude **280.** Resultant **278** is formed after the positive diodes **83, 84** and **85** at terminal **90.** When the negative parts of noise signals **275, 276** and **277** are rectified by diode gates **86, 87** and **88,** inverted, e.g. in an operational amplifier, and combined at terminal **90,** the resultant noise signal is further reduced to a maximum peak-to-peak level **283,** as shown in FIG. **17B.** The deepest "gaps" of signal **278** are filled in by inverted signal peaks **284.**

Thus the resultant noise signal at the common output terminal has an amplitude less than those of the individual noise signals appearing at the output of each amplifier **79.**

a. Uniformity of Response

It was found that aging of both high-vacuum and gas type photocells was essential to obtain long term stability of response in a sensing head. In FIG. **1,** the photocell **13** gives the outline of a Type 5583 gas filled cell. In order to construct a photocell row with associated 1 inch wide optical increments (units), the glass container housing the photocathode had to be less than 1 inch in diameter and had to exhibit a sensitivity for light which gave the currents and voltages described in conjunction with the circuit of FIG. **2.** It was found that a gas filled photocell has to be used with a sensitivity approximately 5 times greater than the corresponding high vacuum cell in order to reach photocurrents of the order of 0.2 microamperes. In spite of an extended aging process lasting 30 to 60 days, the long term stability of the cell sensitivity was only acceptable, but not absolute. It was found that in a 3 to 6 month period, an inspection head system has to be re-calibrated by adjusting moveable aperture member **18.** As the average inspection machine contains over 100 cells, this is a time consuming and arduous operation to be avoided or completely eliminated if possible. It was further found that when a well adjusted inspection machine was resting, i.e., the lamps were switched off for periods of time, the sensitivity of the cathode occasionally exhibited a type of recovery resulting in increased sensitivity. Hence, on an inspection machine when the lamps were switched off for longer periods, the head system had to be re-calibrated or at least re-checked.

Using silicon photodiodes, or phototransistors, or photovoltaic cells (solar cells) complete long term stability is obtained. Such silicon photosensitive devices exhibit no aging whatsoever.

b. Signal to Noise Ratio

As described, the limiting full black spot of a 1 × 0.020 inch optical unit used in pairs with differential amplifiers is a one thirty-second inch full black spot, assuming a reliable signal to noise ratio on the average sheet material having reasonable uniformity. Often it is essential to detect defects with a much smaller diameter. For example, on photosensitive films, a speck hardly visible to the human eye, having a diameter of only 0.003 inch, has to be detected. The limiting defect on papers used for optical character recognition in the readers for computers has a diameter of 0.004 inch with a contrast of only 20 percent. Such a defect cannot be seen by the naked eye, but has to be detected by the optical unit. As the light efficiency using the most efficient fluorescent type illumination cannot be materially increased, the only way it is possible to obtain a percentage modulation of say, 2 percent, is by reducing both the length and the width of the optical aperture; for example, the use of phototransistors with diameters varying from 0.080 to 0.20 inch enables an optical unit design such that each inspected inch of the material is observed by four or eight optical units. A practical compromise would use say, **4** silicon phototransistors Type FPT-100 or MRD-300 using four cells and two differential amplifiers per 1 inch inspected width. Photodiode and phototransistor arrays of much finer definition are also available.

As the basic noise is proportional with the amount of light which falls upon the cell and as the noise generated by the unblemished sheet systems, is reduced by reducing the viewed section in such system, the limiting defect size can be reduced and the signal to noise ratio can be kept above a 3 to 1 ratio. For example, an aperture with an area of 0.25 × 0.010 inch generates eight times less noise and the associated limiting defect is of the order of a 0.010 inch diameter spot.

It was found that in a system similar to that in FIG. **1** with unit apertures of 0.25 × 0.010 inch, with cells located approximately one-half inch above the aperture, the photocurrent obtainable under optimal conditions was of the order of 50 microamperes. This is approximately valid both for phototransistors and solar cells.

An aperture window of 0.005 by 0.050 inch can give a steady current of approximately 5 microamperes and can detect at 3,000 feet per minute web speeds the referred to limiting defect on O.C.R. papers.

c. Noise to be kept an order of magnitude below the useful signal level,
d. The system to be free of interference,
e. Immunity to in-phase disturbances:

The circuit of FIG. 3 improves these requirements when comparing its performance with that of the circuit of FIG. 2.

The differential advantages are preserved by feeding phototransistors **64, 65** from equal positive and negative sources and by interconnecting the emitter of phototransistor **64** and the collector of phototransistor **65** and connecting the so formed junction via resistor **70** to input terminal **73.** When the light falling on phototransistor **64, 65** is equal and their light sensitivity and "transistor current gain" are equal, the potential at input terminal **73** is zero and is not affected by in-phase voltage variations of the supply, environmental light changes, sheet material supporting roller eccentricity, flutter, etc. This is similarly the case for solar cells **68, 69** which exhibit an additional advantage in that supply voltage variations cannot affect the sensing cells because solar cells are photo-voltaic cells generating their own voltage.

As resistors **70, 71, 72** are of the order of 1,000 ohms and as the input terminal **73** is connected through a low impedance to virtual ground, the immunity of the system to capacitive interference pick-up, and vibration is very much better than that of the critical components in the circuit of FIG. 2; in particular the 2.2 megohm resistance of resistor **28** in FIG. 2 is two thousand times more sensitive to capacitive pick-up and has to be well shielded and mounted in a vibration-proof manner.

The small sized operational amplifiers **79** and the few low voltage associated circuit components are best located within the well-shielded inspection head, then the interference problems associated with cable **43** of FIG. 2, are completely eliminated.

The cable connection between the read-out common to many optical units and amplifiers in the head system, containing all components of FIG. 3 multiplied manifold up to terminal **90,** would be between the two common junctions of the positive **83, 84,** etc., and the negative **86, 87,** etc., diodes and two only terminals like **90.**

The pulse forming readout circuit associated with amplifier **93,** any additional amplifier which may be associated with a group of amplifiers like **79,** differentiating and integrating units, the adjustable gate control for the whole system, power supplies, would be located in a control cabinet separated by any desired lengths of cable. The significant improvement in FIG. 3 is that the output impedance of amplifier **79** is very low indeed. It is only of the order of 1 ohm or less. Also, the large number of conducting diodes, both positive and negative, ensure that the two common junctions of the cable termination, like **90,** also have a very low output impedance. Hence, the construction of a cable of any length, free of interference, is ensured, as capacitive or inductive pick-up is substantially eliminated by the very low impedance of the cable terminals.

Immunity to in-phase interference is retained in FIG. 3 and as good as that of FIG. 2.

Requirement (*f*), namely the limited DC gain in the system and requirement (*g*) the near ground DC levels of the amplifier outputs are retained and improved in FIG. 3.

In FIG. 2, the DC gain of two defined by resistor ratios **46** and **47** over **44** can result in a differential DC level of the order of 1 volt measured at the outputs **54, 55.** In order to minimize the effect of this DC level, the gate potential is fixed at 8 volts.

In FIG. 3, in spite of the DC gain of **10,** the output level at diodes **83, 86,** etc., is separated only by a few millivolts from ground. Hence, it is practical to adjust the sensitivity of the system by adjusting the gating level from 12 volts down to, say half a volt. This, in turn, greatly simplifies the design of the amplifier and the number of components associated with it, because the adjustment of the gain of the amplifiers is not required for setting several levels of defect sensitivities.

A further advantage is that the time constant of amplifier **79** is not affected by its A.C. gain, defined by resistors **74** and **78.** The time constant of the amplifying system of FIG. 2 is defined by resistors **46, 47,** capacitor **48** and also by the gain of amplifier **51.** When, in FIG. 2, the gain is changed by a factor of 1 to 40, the time constants changes from 2 seconds to less than half a second. In FIG. 3, the low frequency limitation and associated time constant is defined entirely by resistor **74** and capacitor **75** and is independent of the gain of the amplifier **79** or of any additional amplifier in series with **79,** having adjustable gain.

Last, but not least, the most important advantage of the configuration in FIG. 3 is that the outputs can be combined at very much lower levels and the read-out is reliable above a 50 millivolt level.

Relating to requirement (*h*), namely, that a defect has to be detected when it is lighter or darker than the mean intensity of the inspected material, in FIG. 2, it is never known whether the source of signal was lighter or darker because on both outputs of the differential amplifier the signal appears in either polarity, and both outputs have to be combined.

This need not be the case in the configuration of FIG. 3. Here, certain defects can be separated and recognized by connecting only one cell, **65** or **66,** to the input. Simultaneously, the differential advantages are sacrificed. In some applications, recognition of defect types prevails over other considerations.

The referred to universally efficient optical design of FIG. 4 is disclosed in FIGS. 4A, 4B, 4C, 4D, 4E and 4F.

Universal efficiency for the inspection of all types of materials and defects means; the same design can be employed for the unit-head-sections housing the amplifiers and supporting optimal variants of the lamps and optics;
the same design of the structure supporting the unit-head-sections can be used for inspection machines of any practical width;
the same design can be used when the inspected material is illuminated from the top or from the underside or from both sides;
further, when the width of the inspection machine changes, substantially all dimensions of the design remain unchanged with the exception of the size of the main support beam which gives rigidity to the inspection head system.

Other improved features of the design in FIG. 4 are:
The sheet supports are engineered such that the sheet is carried under the inspection head without flutter, such flutter could cause false modulation of the photo-

cells. Also, the sheet supporting means (when stationary - non-rotating) cannot damage the contacting surface of even the most critical pressure sensitive sheet materials.

In order to obtain optimal definition and performance for defects, the distance between the aperture of the optics and the sheet is adjustable exactly to any desired uniform dimension along the complete width of the widest of inspection machines, and the sheet support surface can be crowned or not as required for best delivery of the sheet material.

In order to avoid cleaning the optics, the head system is pressurized. The design is such that sufficient filtered air is passing through the optical aperture and air loss through leaks is a fraction of the useful flow.

All cabling is neatly protected within the main support beam. The head system is streamlined; plugs, sockets, or cables do not protrude anywhere.

The head system is hinged and can be raised or tilted upwards for convenient servicing to enable the sheet material to be fed through the machine with ease.

The design allows a balanced weight distribution relative to the hinge point so that the slightest force can tilt the head. When automatic or push-button controlled lift of the head system is used, as on most paper machines or coasters, pneumatically controlled air lifting cylinders are added.

The unit head sections to be exchangeable quickly. This is especially important when such systems are attached to paper machines. Any one head section can be changed within 10 seconds.

Hinged circuit board design within the unit-head-sections. This allows the check-out of each side of a printed circuit board, enables repair of electronics. Exchange of individual components without the removal of the head sections is practical.

Accurate alignment of the distance between the aperture and the inspected sheet material. This to be accomplished whether the sheet support is crowned or not. Adjustment of head sections is made possible by a sufficient design of tolerances and clearance holes for the plug and socket connectors, the mounting bolts and air pressurizing inlets for each head section.

Details of the design of FIG. **4** are best described with the aid of FIGS. **4A**, **4B** and **4C**. FIG. **4A** presents essentials of the design by a section in the direction of flow of the material. FIG. **4B** is a view and shows sections of details at right angle to the direction of flow of the material. FIG. **4C** shows details of the universal five inch wide (crossmachine width) unit-head-section with one preferred version of an optical aperture attachment using **16** photo-transistors.

In FIGS. **4A**, **4B** and **4C**, sheet material **1** is illuminated by fluorescent lamps **4, 5** and **6.** Reflected diffused light and transmitted light at aperture **10** is sensed by a row of phototransistors as was described in FIG. **3.**

The sheet material passes over rollers **100** and **99** and under roller **98** which, in tur, as located by ball bearings affixed to frame **112** of the inspection stand. The frame is constructed from rectangular seamless steel tubing with dimensions of 2½ inches × 2½ inches and 2½ inches × 5 inches.

The sheet material is also supported by a 3 inch diameter tubing **118** which has a sufficient opening opposite the aperture such that the viewed section of the sheet material can be uniformly illuminated from the underside. The preferred material for tubing **118** is stainless steel. The position of tube **118** can be adjusted as required by bolts **119** which are preferably welded to tube **118** and are set by adjustable nuts through clearance holes in support beam **120.**

On opaque materials, or on materials where illumination from the underside is not required, rollers **99** and **100** and sheet support tube **118** are replaced by one roller centrally located relative to the aperture. In FIG. **4A**, the outline of such an 8 inches diameter roller is indicated.

A sufficient wrap such a roller completely eliminates the tendency for the material to flutter because the sheet is stretched sufficiently across its whole width. Even on materials which exhibit soft edges or loose central sections, the wrap as shown in FIG. **4A** over an 8 inch diameter roller can be relied on to stretch out the material.

An alternative design to eliminate flutter is the tube support **118.** In order to eliminate damage by friction on some sensitive materials this tube is pressurized by air.

The air inlet can be located at any convenient point through a flexible tubing. It can be shown that at usual web tensions, which vary between 1 to 5 pounds per lineal inch, an air pressure of less than 1 pound per square inch is sufficient to completely lubricate by air the surface between the support tube and the sheet. Such air lubrication is possible with a very minimal flow of air. On some materials, where damage due to the contact between the polished support tube and the material cannot occur, instead of pressurizing, a moderate amount of vacuum can be used to ensure complete elimination of flutter of the material.

The head system is supported by adjustable end brackets **111.** The head system consists of unit-head-sections **101,** main support beam **106,** air pressurizing distribution tube **116,** aperture casting **102,** lamps **4** and **5,** covers **104** and **127,** support hinges **110,** securing clamp **131,** and other internal details to be described.

The unit-head-section **101** is housed in and supported by a high grade aluminum standard angle section with dimensions of 6 inches × 2¾ inches. This "housing" does not require refinishing except to be slit with tolerance into the required **5** inch wide sections as seen in FIGS. **4B** and **4C**, and then exactly milled to the 5 inch dimension and tied together practically air-tight by simply mounting these sections of the housing by two bolts **107** per section to the main support beam **106.**

The nut counter parts of bolts **107** are tapped into beam **106.** The corresponding clearance holes in members **101** enable the fine adjustment of the unit-head-sections such that apertures **10** are in exact alignment and are at the same distance from the sheet material.

The aperture body **102** is preferably an injection moulding of suitable metal composition to give precision finish, or could be a precision aluminum sand casting. In the latter case, the aperture opening **10** is conveniently cut out with a circular saw on a milling machine. As seen in FIGS. **4A** and **4C**, each moulding **102** is secured by four bolts **103** through clearance holes **125.** Clearance holes **125** allow exact alignment of the mouldings or aperture castings **102** to form a sharply defined continuous inspect line. The castings are also

grooved to locate springs **123** which hold lamps **4** and **5**. The **5** inch wide head sections are divided into 1¼ inch subsections when the type of phototransistors **122** used have a diameter of 0.20 inch.

Such phototransistors are best plugged into holders **121** with gold-plated contacts which locate in holes having a diameter of 0.25 inch. There are **16** photocells in each 5 inch wide unit-head-section, spaced 0.3125 inches apart. Between each photocell there is a metal rib of 0.040 inch thickness which shield optically the cells and also hold the aperture sides together, forming a single moulded or cast unit.

The amplifiers as per FIG. **3** are mounted on a printed circuit board **105** fixed to a hinge such that the board can tilt forward making both the printed wiring side and the components side of the board accessible for checks and repair. As each board occupies approximately five-eighths inch in the direction of sheet flow, in the available space of 2¼ inches within the housing of the unit-head-section, three such boards can be comfortably located. As each board is processing the output of **16** cells, the total number of cells which can be used within each **5** inch head section is **48.**

The connections leading from board **105** to the control cabinet are via flexible wires to plug **108** which mates with socket **109.**

In order to remove a unit-head-section, the cover **104** (covering four to six head sections) is removed, the securing screw at the top of the printed circuit board is released, the board is tilted forward, plug **108** is pulled out from socket **109** and two bolts **107** are unscrewed. This is an easy and quick operation.

In order to make the head system insensitive to vibration, thermionic tubes and photocells were replaced by silicon semiconductor type devices. Vibration, sheet flutter or movement of the sheet relative to the aperture could cause variation of light entering through the aperture and falling on the phototransistors. In order to make the system insensitive to such disturbances, the design of the collimating noise of the aperture casing (moulding or casting) **102** is such that any light ray emanating from the lamp should be blocked in the least possible way by the noise section of the casing. For example, in FIG. **4C**, the distance between sheet and aperture **128** or **129,** should be such that the illuminated section of the sheet (illuminated by all beams), **130** for example, is wider than what the photocell through the collimating system can see. For example, the central chip of an FPT-100 type phototransistor is approximately 0.050 by 0.050 inch. This chip viewing the sheet through aperture **10,** which is, say 0.010 inch in the direction of flow, would result in a width for the inspect line, that is a viewed line width in the direction of flow, of approximately 0.015 inch at sheet position **128** and 0.030 inch at sheet position **129.** It is easy to see that for sheet position **129,** the width of the uniformly illuminated line **130** is nearly one-eighth of an inch. Also, in this design it can be shown that when the lamps are fixed and the head section with the aperture is moved upwards, the amount of light collected by the cell is substantially constant for movements varying from the distances shown at **128** or **129** up to 0.5 of an inch. This means that while the solid angle gets considerably greater as the head section is raised one-half an inch, the uniformity of the light intensity of the surface of the sheet is such that the amount of light collected by the active chip of the phototransistor remains constant.

Air pressurizing is done through distribution tube **116** via one opening **117** for each head section. Again, head section adjustment won't interfere with the flow because the corresponding hole in member **116** is larger than the air entrance hole **117.** As shown in FIG. **4C**, air flow into the collimating nose is ensured by six holes per section designated by number **126.**

Angle **106** supporting the whole head system is 5 inches × 2½ inches × ¼ inch wall in FIG. **4A**. This angle is sufficient for an inspection machine up to 60 inch width. Between 60 and 100 inches, an 8 × 3 × 9/**32** inch wall is used for member **106.** Between 100 and 160 inches, a 10 × 3½ × 5/**16** inch wall angle is used; and above 160 inches, a 12 × 4 × ⅜ inch wall angle is used. The essential part of the design is that for all sizes of angles forming the support beam, the location and dimensions of hinge **110,** bolts **107** and connecting socket **109,** remain constant. The only item which would be modified is the skirt of cover **127.**

For accommodating 4 inch diameter or 8 inch diameter rollers support brackets **111** at each end of the inspection stand are raised by using one or two locating holes **113, 114, 115** and simply raising or lowering the brackets as required.

In order to obtain optimal signal to noise ratios, in FIG. **4B** it is shown that lamp **6** can be adjusted up and down within tube **118** and thus defining the intensity of the background for the sheet material.

The number of adjusting bolts **119** used for defining the position of the sheet support tube **118** depends on the width of the machine. The strength and rigidity of the support tube **118** depends on the strength of the beam **120.** In FIG. **4** beam **120** is made of seamless square tubing with dimensions of 2½ inches × 5 inches. This beam looks after inspection machines up to 140 inch widths. For wider machines, the 5 inch dimension increases.

The often used variant of the aperture casing (moulding or casting) is shown in FIGS. **4C/D** and **4E**. FIG. **4C/D** is a repeat of and shows only essential outlines of the aperture casing defined in FIGS. **4C** and **4D**. A slim and blunt design for the nose of the aperture casing is shown in FIG. **4F**. The significance and the effect of the nose design upon the optical efficiency, definition, insensitivity to vibration and uniformity of sensitivity in the cross-machine direction of the optics is explained with the aid of FIGS. **5A, 5B** and **5C**.

An alternative aperture housing design is shown in FIGS. **6A** and **6B**, also presenting a method of locating either phototransistor or photovoltaic cells in the standard base member of the unit-head-section **101.**

There is a third basic aperture casing design the shape of which is similar to that of FIGS. **4C/D** and **4E**, but in which each side of the aperture casing is adjustable, and the optical units are not separated by metal ribs.

The aperture casing of FIGS. **4C/D** and **4E** forms, as was hereinbefore described, a single moulding or casting. The two sides of the aperture casing **102** are connected by ribs **132,** forming distinct compartments for each optical unit, as seen in FIG. **4E**.

The pitch of the optical units, i.e., the distance between ribs **132,** is 0.3125 of an inch.

It is essential that light emanating from any point at the inspect line beyond the half pitch distance of an adjacent optical unit shall not reach cell **122,** as seen in FIG. **5C**. This enables pairs of non-adjacent cells to be

connected to a differential amplifier and optimizes the signal-to-noise ratio of an optical unit, minimizing the image size in the cross-machine direction.

The dimension of rib **132** terminated near the aperture opening **10** is such that a minimum sized defect located opposite the rib, that is between two optical units, shall be fully seen by the photosensitive silicon-chip **134** of phototransistor **122.** It is seen from FIG. **5C** that the solid angle formed by the extreme beams emanating from a minute defect in the center of the optics (lying in the center line in FIG. **5C**) is substantially the same as the solid angle emanating from the extreme edges and formed by lines **142** or **143.** Hence, the sensitivity of an optical unit as shown in FIG. **5C** is substantially uniform in the cross-machine direction.

In order to eliminate secondary reflections due to light beams emanating from the inspect line beyond those numbered **142** or **143,** the internal parts of the aperture casing are made optically black. This is best done by etching and anodizing or by etching or sand-blasting and spray-painting matte optical black paint over all the internal surfaces.

The best application of the slim and blunt nose design as shown in FIG. **4F** is explained with the aid of FIGS. **5A** and **5B**. The slim nose is best produced by precision injection moulding. The extreme end of the nose has a dimension of 0.018 of an inch against a dimension of the blunt nose of 0.054 of an inch. It is possible to produce a sufficiently precise sandcasted blunt nose; the end of the cast nose is milled and cut by saw.

The extreme light beams **139, 140** or **141** emanating from the lamp have to illuminate the sheet material beyond the width of the inspect line. In FIG. **5A** or **5B**, the inspect line is defined by the dimension of the aperture **10** at the extreme end of the nose (beams **138**) and by the attenuated skirts at each side of beams **138** bordered by beams **137.** The width of the inspect line defined by beams **137** is substantially identical for both designs **5A** and **5B**. It should be noted, however, that the extreme beams, emanating from the lamps (lamps contacting aperture casing), **139** in FIG. **5A** and **140** in FIG. **5B**, clear the inspect line in the case of a slim nose and do not even reach the centre of the inspect line in the blunt nose design. Hence, in order to obtain uniform illumination of the inspect line free from vibration modulation when the inspected material is located close to the aperture and is at distance **128** for obtaining fine definition in the direction of flow, in the blunt nose design the lamp has to be moved away from the nose until the extreme beam **141** does not cross through the inspect line.

In FIGS. **5A** and **5B**, it can be also seen that when the definition requirement is reduced and the sheet material is placed at a distance of 0.2 of an inch from the aperture, as indicated by number **129,** the lamp positioned closest to the nose radiates an extreme beam **140** which clears the wider inspect line.

When fine definition is essential, for example when the width of the inspect line should be substantially equal to 0.010 of an inch, as defined by sheet position **128,** the slim nose design is more efficient. and is least affected by a type of vibration which produces displacement between the lamps and the aperture casing.

In order to sharpen the definition in the direction of flow, the depth **136** of the aperture channel assists. Only beams emanating from the sheet surface between light beams **138,** that is beams emanating from a 0.010 of an inch wide section, are free from attenuation. Hence, the sensitivity curve shows a flat top for a sheet movement of 0.010 of an inch and is attenuated quickly for the further movement of approximately 0.003 of an inch. However, it is important that the aperture channel **136** has a non-reflecting optical black finish. There are some practical difficulties in producing such an internal surface; hence the optimal design features described may suffer due to secondary reflections from aperture channel **136.**

When the sheet material is close to the blunt nose at a distance **128,** secondary reflections can be completely eliminated, the optical efficiency is good and the definition approaches that of the slim nose design; however, its use is only advised when the material is matte and produces substantially diffused reflections.

For fine definition on shiny materials, when the reflected energy entering the optical unit is quite dependent on the angle of incidence of the light beams, the blunt nose design of FIG. **5B** is not recommended. On such shiny or glossy materials, the larger distance **129** should be used when associated with a blunt nose design.

As seen in FIG. **5C**, the sheet distance **128** or **129** does not affect the uniformity of sensitivity of the optics in the cross-machine direction. Naturally, the size of the limiting defect is approximately 3 times greater in area for the distance **129** than for the distance **128.**

Often it is undesirable to have high sensitivity at the 0.010 inch diameter spot limit, in which case the blunt nose design is preferred because it gives cleaner optics free from aberrations and secondary reflections and is less critical to make.

The aperture casing design of FIGS. **4C, 4D, 4E, 4F, 5A, 5B** and **5C** is used for substantially all materials, opaque, transparent, glossy, and matte, and for all types of defects caused by foreign substance like dirt, inclusions, abnormal transparencies, holes, creases, lumps, coating discolourations, streaks, etc., i.e., for defects which produce a contrast against the mean background.

There are certain materials like transparent glass film or plastics which exhibit defects not associated with foreign bodies, etc., but which show nonuniformity due to, say, a transparent coating streak (missed coating) or bubbles or fine scratches, i.e. defects which are hardly visible under normal illumination. Such materials are best examined for uniformity of transparency using underside illumination only. Hence, lamps attached to the inspection head system are not required and a simplified design for the aperture casing, shown in FIGS. **6A** and **6B**, is possible.

In FIG. **6A**, the aperture casing is constructed from rectangular plates **144** with adjustable aperture forming plates **145** (adjustable relative to members **144**). (Members **144** are also adjustable within the tolerance of clearance holes **125**; see FIG. **4D.**)

This design would assist the manufacture of near-perfect internal optically black surfaces as each piece (**144, 145**) can be prepared, etched or sandblasted and painted, etc., separately.

Also, the construction of internal ribs is eliminated because the source of illumination shown by beam **151** entering aperture **10** and falling upon cell **148** is formed from near-perfect parallel light beams. For ex-

ample, a tungsten halogen lamp, say 5 inches in the cross-machine direction and one-half inch in the flow direction can be placed 10 feet (120 inches) from sheet material **1** to form such parallel lighting.

Every point of the sheet material forming the illuminated inspect line, viewed through aperture **10** by cell row **148,** forms an image on one of the cells which is only slightly greater than the dimension of the referred to point on the sheet material. Hence, unnecessary light beams which produce increased signal-to-noise ratio are not present.

For example, a spot corresponding to an infinitesimal speck on the sheet material would appear in the direction of flow having a dimension of 0.005 of an inch at the cell surface and would appear 0.050 of an inch wide in the cross-machine direction because the distance of the cell from the sheet material is approximately 1.2 inches while the distance of the lamp from the sheet material is 120 inches. Hence, when calculating the smallest spot size, the lamp dimensions are reduced by a factor of 100.

As an example, in FIGS. **6A** and **6B** photovoltaic cell units are shown which are 2.24 millimeters wide in the cross-machine direction and 5 millimeters wide in the direction of flow. Thus, the 0.3125 inch pitch of the cells in FIGS. **4D** and **4E** can be divided by a factor of 3 resulting in a pitch between cells of 0.104166 of an inch forming a row of 48 cell units in the 5 inch wide unit-head-section and increasing the definition for minute defects considerably.

The aperture casing design and the parallel lighting system of FIG. **6** would be the most sensitive system for transparent materials using the universal head design.

In order to eliminate secondary reflections and noise, shading members **154** limit the width of the illuminating beam to one-half inch on the sheet and shade noise producing reflections from the sheet carrying rotating bodies of rollers **146, 147.**

The system of FIG. **6** performs efficiently by producing a Schlieren type effect, that is emphasizing by a combined diffraction and refraction effect thickness changes at the edges of streaks due to coating imperfections. The mounting of photovoltaic cells **148** by clamping members **149** (preferably made of teflon) and split tubing **150** enables the lowering and raising of the photovoltaic cells **148.** There is an optimal distance to detect modulation of a parallel beam due to diffraction. For a very sharp and fine coating line, the distance between aperture **10** and cell **148** may have to be raised several inches.

The aperture casing design of FIGS. **4C/D** and **4E** can be simplified by keeping the shape of the nose substantially the same as was shown in FIG. **4F,** but eliminating the connecting ribs. Each side is adjustable and the aperture can be set as required between say, 0.002 of an inch and 0.01 of an inch. By using phototransistors, for example, each having a narrow angle view of say 15 degrees and by placing these cells close to the nose, ribs **132** are not required. Pairs of cells can be associated with differential amplifiers or used individually with operational amplifiers. Variants of the aperture casing design **4C/D** which do not require the use of interconnecting ribs **132** are shown in FIGS. **7A, 7B, 7C, 7D** and **7E.** These variations use fiber optics which eliminate interaction between the optical units (a function served previously by the metal ribs), improve the optical efficiency, the definition and the cross-machine uniformity of the optical units.

Use of fiber optics in visible range and in infrared inspection systems for photosensitive materials, when attached to the standard unit-head sections, is explained with the aid of FIG. **9** which shows a lamp and filter design using the aperture casing of FIG. **7B.**

FIG. **8** shows the infra-red lamp and filter design using the standard aperture casing of FIG. **4C/D.**

FIG. **7A** shows in 10-fold enlargement a nose design using fiber optics, sheet material **1** being illuminated with either the standard fluorescent lamps of FIG. **4C/D** for inspection in the visible range, or by infra-red lamps through infra-red filters as per an arrangement in FIG. **8,** for the inspection of photosensitive materials and metals.

FIG. **7B** shows in 10-fold enlargement an alternative nose structure for an aperture casing design using fiber optics where the shape of the nose does not limit in any way the uniform illumination of the inspect line and the distance **128** of the sheet from the aperture. The sheet is illuminated through fibers **158,** which extend to any convenient length to reach a lamp, the position of which is not controlled in any way by the aperture design; for example fibers **158** are illuminated by lamp **176** as shown in FIG. **9**

FIG. **7C** shows a cut through the fiber optics of FIG. **7A** in the cross-machine direction. The cut through the fiber optics of FIG. **7B** is substantially identical, only the diameter of the fiber bundle facing the cell is smaller.

FIG. **7D** is a view of the nose structure of FIG. **7A** as seen from the direction of the sheet material.

FIG. **7E** is a similar view of the nose structure of FIG. **7B.**

The nose structure defined by FIGS. **7A, 7C** and **7D** forms, for example, fiber apertures which are 0.010 of an inch in the direction of flow and 0.3125 of an inch in the cross-machine direction, that is identical with the aperture units of the standard nose structure of FIG. **5** (A, B and C). The inspect line width is substantially identical to that of FIG. **5.** The refraction coefficient and finish of the fiber aperture is such that it can see less of the inspect line than defined by extreme light beams **139.** The angle of the beam spread of the fibers is 8° as indicated by the angles formed by light beams **160** and beams perpendicular to sheet **1.**

The distance **128** of the sheet material from the aperture is again 0.075 of an inch, as was defined in FIG. **5.** Each side **102** of the aperture casing forms a single unit by bonding material **159** which also locates centrally the fiber bundles **156.**

The diameter D of the fiber bundle, having a circular shape at the phototransistor, diode or photovoltaic cell, can be calculated by equating the area of the fibre bundle with the area of the aperture unit:

$\pi D^2 = 0.3125 \times 0.010$ of an inch

$D = 0.0315$ of an inch

Allowing for tolerance in bundling

D = approximately 0.035 of an inch.

The reduction of the aperture unit length of 0.3125 of an inch to a diameter which is approximately one-tenth of this length and the resulting shape is seen in FIG. **7C.** As long as the length of each fiber is the same, the cross-machine direction uniformity can be made substantially uniform. Also, the light efficiency, that is the light being collected from the sheet and transmitted to

the active chip of the phototransistor or photovoltaic cell is better than in the previous design. There is some loss in transmission through the fibers and the manufacture of the fiber bundle itself is a complication, however this design presents features which are not present in previous designs. Air pressurizing is not required. The definition in the direction of flow can be made optimal, especially in the design of FIG. 7B, where the distance **128** of the sheet from the aperture could be made less than 0.075 of an inch. The overlap of the optical units in the cross-machine direction can be controlled exactly; for example, the 12° angle **167** at the borders of the optical units allow an overlap **166** or 0.020 of an inch beyond such borders of each unit; this overlap would match a definition for an 0.010 of an inch diameter full black spot or equivalent defect.

Equivalent defects are defined by the equality of the products of defect area times defect intensity. For example, using integration of the defect intelligence, the overlap **166** of 0.020 of an inch allows the detection of a faint spot centred on the borderline of the optical units with a diameter D1 of 0.040 of an inch and an intensity of **6.66** per cent of full black, when the full black spot detection limit is set to a spot with diameter D2 of 0.010 of an inch.

Expressed in mills:

$\pi^{D1^2} \cdot 6.6/100 = \pi^{D2^2} \cdot 100/100$

$\pi^{(40)^2} \cdot 6.66/100 = \pi^{(10)^2} \cdot$

$1600 \cdot 6.6/100 = 100$

The variant of the nose structure shown in FIG. 7B suits the finest definition in the direction of the sheet flow. The aperture can be reduced to a dimension which is of the order of 0.001 of an inch. Here the sharp shaping of the nose can be eliminated because the light is not blocked by the nose but enters through a fiber bundle **158.** The aperture size of the light emitting bundle can be, say 0.3125 of an inch long and 0.005 of an inch wide. The sheet surface can be placed closer than the previous limit of 0.075 of an inch.

In order to obtain sufficient overlap at the edges of the optical units, the aperture end of the light emitting bundle is also shaped as shown in FIG. 7C, forming angle **167** to the plane of sheet **1.**

It should be noted that the sheet material **1** is not at right angles to the axis Y—Y of the nose structure but is tilted and the axial beams like **164** are accordingly reflected as shown by beam **165.** The spread of the beam at the photocell end is defined by beams **161,** defined again by an angle of **8** degrees formed with the beams parallel to the axis of the fibers. It can be seen in FIG. 7A and 7C that all the light emanating from the fiber bundle is not collected by the active chip **134** of phototransistor **122**; hence, in this application a larger active area, say, of a photovolatic cell **148** is used.

When the aperture is only 0.005 of an inch wide, as seen in the variant of FIG. 7B, the diameter of the bundle near the cell (with tolerance) is 0.0236 of an inch and, as drawn in FIG. 7B, all the beams can fall on the active chip **134** of phototransistor **122**; however, apart from mounting accuracy of the device itself, the central accuracy of the silicon chip in such devices cannot be relief on to better than ±0.010 of an inch; hence, again it is better to use the larger area of a photovoltaic cell to ensure that all the light beams are converted into useful signals. By this arrangement specularly reflected beams are noted seen by the photocells. The sensing of specular beams would make an inspection head system of this type very critical to vibration and to the slighest up or down or angular movement (flutter) of the sheet surface.

Accordingly in FIG. **9,** sheet material **1** travels over raised roller **100** and roller **99,** the position of the latter is is the same as in FIG. **4A.**

One particular means to provide ample and high intensity illumination through the fiber optics is indicated in FIG. **9.** The inspection system shown in FIG. **9** is substantially identical to that of FIG. **4A**; the exceptions are the aperture casing with blunt nose, details of which were shown in FIG. 7B, and the tungsten lamps **176** which illuminate through openings **175** the transparent or matte plate **175** made of polished or ground glass or plastic material.

Using fiber optics, air pressurizing of the head system is not required as the aperture casings and unit-head-sections are fully sealed. Channel **116** which was previously used for air distribution for pressurizing can now be used for sufficient cooling of high power tungsten lamps **176.** A sufficient amount of air can enter at one end of piping **116** and exit at the other end. By this means, projection type tungsten filament lamps consuming several hundred watts each can be effectively cooled and produce exceptional brightness on the inspection surface through the fiber bundles.

For fine definition sheet **1** could practically contact the fiber aperture. It can be shown that when one bundle **158** is associated with each optical unit, the 5 inch wide unit-head-section can be serviced by 16 bundles. The diameter of each bundle is approximately 0.025 of an inch. By making the length of each bundle approximately 6 inches long, 16 bundles can be comfortably located in an area which is

$16 \times 0.025 \times 0.025$ of an inch $= 0.1 \times 0.1$ of an inch $= 0.01$ square inch.

The window **175** in FIG. **9** has an area of approximately **1** square inch. Hence, theoretically, **100** five inch wide unit-head-sections could be illuminated by a single lamp **176.** The excessive length of the fibers serving a 100×5 inch $= 500$ inch wide machine would be quite impractical and associated with varying transmission losses. However, it is quite practical to use say, 12 inch long fibers and illuminate two 5 inch units, that is 10 inches in the cross-machine direction, from one tungsten lamp.

The transparent or diffused plate **175** can be replaced by an infra-red filter, for example, by Corning filter type CS756. Then the system becomes an infra-red inspection system suitable for substantially all types of black and white and coloured films and paper. One of the major advantages of such an infra-red system is that a few filters, 1 inch square in area or less, can look after quite a wide inspection machine, say 100 inches wide. As the infra-red source **176** is completely enclosed within channel **116,** the lighttight sealing of the tungsten lamp can be easily accomplished. Channel **116** is either provided with covered entrance holes for insertion of the lamps, or alternatively the lamps are inserted from their socket end located in the main support beam member **106.**

Usually, the removeable aperture casing **102** is permanently attached to fiber bundles **158** and infra-red filter **174**; hence, the whole system can form a solid block for easy attachment to the infra-red inspection head system.

In FIG. 8, standard air pressurized aperture casings attached to standard unit-head-sections are shown in outlines only. This standard system can be converted to an infra-red system by the use of infra-red lamps **168, 173** and filters **171, 172.** Conveniently, type CM1866 infra-red lamps are used. These lamps are housed in glass tubes with diameters of three-sixteenths of an inch and are approximately 5 inches long with central windows 3.25 inches long. The axially positioned tungsten filaments **169** are stretched straight by internal springs. The lamps have cooper housings and copper reflectors **170.** The active length of the filaments is approximately 3 inches.

Hence two lamps on each side of the aperture nose, that is four lamps per unit-head-section, are used.

The approximately 1 inch distance of the lamps from the inspect line is necessary to eliminate light modulation due to the vibration of the filaments.

The lamps are displaced such that the inspect line is illuminated substantially uniformly for each unit-head-section; lamps **168** would be placed opposite and in line with lamps **173.**

Infra-red filters **171** and **172** (Corning type CS756, for example) can be positioned in a light-tight manner either as shown on the left side of the aperture nose or as shown on the right side. As the extreme beams from the lamps (not blocked by the aperture nose) must impinge upon the sheet material beyond the inspect line, an optimal position for the infra-red filter is one where the filter is not located too close to the lamps and its light-tight fixing and sealing beads are not interfering with said extreme light beams. Such an optimal position for the I.F. filters **171, 172** lies between the possible extremes shown in FIG. **8.**

The channels formed between the infra-red glass filters **171, 172** and the aperture casing **102** can be cooled as required by an air flow. The air is best entered at one end of the head system and exits at the other end. Air distribution channel **116** is used as hereinbefore described for the pressurizing of the head units.

There are several variants of aperture casings which can be regarded as abnormal units used only for very special applications.

In what follows two such special applications are described: dirt particle counting in pulp board and in O.C.R. papers, and the detection of faint coating lines or fine scratches which flow in an uninterrupted and uniform manner exactly in the direction of the sheet material flow.

When inspecting papers used in readers for optical character recognition in computers, the detection of minute specks of the order of 0.004 of an inch diameter with a limiting contrast of 20 percent of full black is required. Said minute dirt speck, passing by two standard aperture windows 0.3125×0.010 of an inch connected in a differential manner to an operational amplifier as per FIG. **3,** would result in modulation of the light which is considerably less than 1 percent. In order to detect such tiny pecks, hardly visible to the eye, the aperture window area has to be reduced by at least a factor of 10. For example, the aperture window dimensions are made 0.050×0.005 of an inch and only one optical unit is connected to an operational amplifier, thereby increasing its sensitivity or the percentage modulation of light by approximately 20-fold.

The construction of such an aperture casing could take the shape of several of the previously described types. The aperture casing design of FIG. **10** uses fiber optics for particle counting. The significant difference in FIG. **10** is that the inspection system using the standard unit-head-sections would see only one-sixteenth of the material when the pitch of these optical units with reduced aperture size is the standard 0.3125 of an inch. It was found that the arbitrary distribution of dirt particles is uniform across the web; hence a statistical sampling technique multiplied by a number (which is approximately 6) gives reliable dirt counts.

FIG. **10A** can represent a cut in the cross-machine direction of the aperture casing which was shown in FIG. 7A or FIG. 7B. The same numbering is used in FIG. **10A** as in FIGS. 7A, 7B, 7C and 7E.

Only the length of the active aperture, 0.050 of an inch, and the diameter of the fiber bundle, being 0.010 of an inch, opposite the silicon chip **134,** is much reduced when a comparison is made with FIG. 7C.

FIG. **10B** is a view seen from the direction of the sheet material.

According to the O.C.R. reader system, lamps in the visible or infra-red spectral range are used.

The inspection of coating lines and scratches, especially when such are faint, is best done through apertures which are parallel to the coating lines, i.e., to the direction of the sheet flow. Hence the standard optical apertures of 0.3125 of an inch by 0.010 of an inch (or 0.005 of an inch or even less) are turned at 90°.

In FIG. **11,** which is one of several practical designs, the apertures and lamps are separated from the standard head system housing the amplifiers, and are made to oscillate in the cross-machine direction with an amplitude greater than the distance between cell units. Illumination for opaque materials is from the top using fiber or other optics, for transparent materials, from the underside. In th latter case, stationary lamps can produce uniform illumination in the cross-machine direction, alternatively light emitting diodes are use which oscillate in unison with the aperture structure.

The oscillating aperture systems for the detection of coating lines or scratches in the direction of web flow are described in FIGS. **11A,** B, C and D

In FIGS. **11A** and B the inspected material is illuminated through fiber optics. FIGS. **11C** and D use lamps; such lamps can be located in any position. In FIGS. **11C** and D the axis of the lamps are in the cross-machine direction and the lamps are displaced on either side of the aperture casing.

The oscillating aperture casing system in FIG. **11A** is separated from the standard head system proper, defined by members **101, 104, 116,** etc., by co-axial cables **182** and fiber bundles **158** which can be several feet long. The distance **187** of the oscillating aperture casing from the head system is made, say, conveniently two feet long.

The distance **187** is defined by two requirements: the amplitude of oscillation of the aperture system and the elasticity constants of the fibers and wires contained in co-axial cables **182** and fiber bundles **158.** Obviously when the amplitude of oscillation is relatively small, say 1¼ inch (twice the optical unit pitch of 0.625 of an inch), the distance **187** may be made only 10 inches. The essential consideration is that none of the fibers and wires in the interconnecting system should reach a

bending force which would approach the elasticity limit.

Apertures fromed from fibers **157** are approximately three-eighths of an inch in the direction of flow and can be only 0.005 of an inch in the cross-machine direction. Thus, a fine coating line or scratch will produce a large percentage of modulation as the aperture crosses this type of defect.

The material is illuminated through fibers **158.** According to the required light intensity and the illuminated window area of plate **174** for obvious practical reasons, the dimensions of illuminating apertures **158** are three-eighths of an inch in the direction of flow and are made as thick as possible in the cross-machine direction. Fibers **158** are shown in FIG. **11B** to be approximately 0.060 of an inch. If the deckle of the web is wide, say, 60 to 100 inches, the tendency would be to reduce this dimension to 0.020 of an inch so that a relatively large number of fiber bundles **158** can be combined at the window **174** which, through opening **175,** could use the efficient tungsten lamp **176,** which was shown in FIG. **9.**

In FIG. **11A,** the sensor **122** is a phototransistor, plugged into socket **121** which, in turn, is connected through co-axial cable **182** to the standard amplifiers housed in unit-head-sections **101.**

Both the co-axial cables **182** and the fiber bundles **158** are firmly held by silicon rubber grommets **184** located in cover plate **183.** Co-axial cable **182** and fiber bundles **158** are similarly firmly held in the stationary head system by silicon rubber grommets **184** and silicon rubber plug **178** (GE Siliconex or Dow-Corning RTV). As many fiber bundles as possible and as is practical are collected opposite window **174;** in FIG. **11A,** for simplicity, only one bundle associated with a limited section of the oscillating aperture casing is shown.

The window **174** can be an infra-red filter or a transparent or ground glass plate. The fiber bundles and the window are held in position by bracket **177.**

The aperture nose formed by aluminum angles **179** is made long enough to accommodate the easy forming of the fiber aperture **157.** Member **180** supports the aperture nose, the photosensors and aluminum angles **181.** The height of angles **181** is changed according to the width of the inspection system. These angles give rigidity and strength to the oscillating system. For example, for a 60 inch wide system, the height of angles **181** is 6 inches.

The oscillating aperture system is supported by teflon rails **185** located in brackets **186** which are attached to the side frame of the inspection system. In FIGS. **11A** and B, the inspected material **1** passes over roller **188.** Several alternative support structures can be used; the design is governed by the opacity of the inspected material.

In FIGS. **11C** and **11D,** material **1** is illuminated by lamps **168** and **173.** These lamps can be the identical CM types disclosed in the description of FIG. **8,** i.e., with 3 to 5 inch active tungsten filament lengths centrally located in approximately one-fourth inch diameter glass tubes with copper reflectors, efficient in the infra-red regions.

In order to illuminate the inspected material effeciently, the aperture casing **190** is raised five-eighths of an inch above the web **1.**

In order to illuminate web **1** uniformly, lamps **168** on the left side of the aperture casing are not positioned opposite lamps **173** on the right side. For example, when the active length of the filaments in each lamp is 5 inches, lamps **168** are also displaced in the cross-machine direction by 5 inches, relative to lamps **173.**

in order for the phototransistors **122** to see only a sharp and long image defined by lines **196,** lenses **189** and adjustable aperture plates **192** are used. It can be shown, using the Lens-Maker's Equation $1/i\ F = (N - 1)\ (1/R1 + 1/R2)$, that using an 0.020 inch wide aperture in the cross-machine direction, and sphere-radii of one-fourth of an inch for a double-concave "thin" lens, the width of the image **196** is of the same order of magnitude as the width of the aperture.

F = focal length

N = co-efficient of diffraction = 1.5

$R1 = R2 = ¼$ inch

$1/F = (1.5 - 1)\ (4 + 4) = ½\ (8) = 4$

$F = ¼$ inch.

By placing the aperture close to the silicon chip of the phototrasistor and at a distance 2F, one-half inch, from the central plane of the lens, and the sheet approximately the same distance away from said plane, the image has the same dimensions as the object, i.e., the aperture.

Lenses **189** are firmly held in concave grooves by metal spacers **191** and the grooves match the sphere of the lenses, milled into members **190.** There are silicon rubber or P.V.C. paddings between the glass or plastic lenses and spacers **191.**

Spacers **191** also hold aperture case members **190** firmly together, using screws **194.**

The U-shaped aperture plates **192** are a tolerance fit within casing plates **190.** Plates **192,** and hence the aperture position facing the silicon chip of phototransistor **122,** is adjustable by first slackening, then tightening one of a pair of screws **193.** One of the screws of a pair **133** is locked, hence when the other of the pair is slackened, the locked screw allows fine adjustment of the aperture position.

For clarity the mounting of lamps **168, 173** in spring clips is not shown.

Apart from the lensed aperture nose, the other member of the oscillating systems such as support plate **180,** angles **181,** cover plate **183,** co-axial cables **182,** teflon covered rails **185, 186,** grommets **184,** are identical in design and dimensions to the identically numbered members in FIGS. **11A** and **11B.**

On uniformly located or finished materials the amplifiers and read-out circuit use the configuration of FIG. **3.**

When the material is not uniform, exhibiting formation or streakiness, the reliable detection of coating lines is enhanced by feeding the output pulses, developed in the circuit of FIG. **3,** through digital logics which only give an output when several consecutive crossings of the coating line or scratch always give a signal. It is also useful to make the output of the system active only during the central parts of the amplitudes of oscillations, i.e., during the central near linear movement of the sine wave function - which corresponds to the oscillations when such is drawn on the Y axis against a linear x time base.

To serve this purpose the output of the system can be gated, opened during the linear central section of said sine wave, and closed during the peak periods, by say, using a lamp, aperture and phototransistor combina-

tion. For example, by making the gate controlling aperture dimension in the cross-machine direction five-eighths of an inch and the peak-to-peak amplitude of the oscillations 1¼ inch, the output signals are only available during the central five-eighths of an inch movement. As the pitch of the optical units, lenses, photosensors, etc., is five-eighths of an inch, all the material is examined for coating lines and scratches. There are no blind spots. To overcome signal generation by formation or streakiness, the output of the amplifier is best differentiated, i.e., passed through a high-pass filter or a band-pass filter.

Differentiation, integration, summation, low light level phototransistor circuits and defect size selection is dealt with in more detail in what follows.

In order to detect all types of defects, large and faint defects and minute, sharply-defined defects, the effectiveness of the circuit of the operational amplifier **79** in FIG. **3** can be improved by amplifying the signal intelligence also with a differentiating amplifier. This is disclosed by FIGS. **12A**, **12B** and **13.**

Let the time constant of amplifier **79** in FIG. **13**, formed by resistor **74** and capacitor **75**, be 1 second. (Then the capacitance of capacitor **75** is 100 microfarad.)

The oscillogram in FIG. **12A** is generated by the moving inspected material. Voltages e are measured at the output of the operational amplifier **79.** The non-defective material is not uniform and generates noise signals **197** with a low frequency content. The readout level **199**, set at gate voltage level E1, is adjusted to be three times higher than the rectified peak-to-peak noise signal **197.** A large, faint defect is indicated by signal **202.** Signal **202** is above the gate level, hence a defect output signal results. The signal **198** is generated by, say, a fine scratch. It is fast, its rise and fall time is short and its frequency content is much higher than the frequency content of the other signals in FIG. **12A.** Defect signal **198** cannot be detected because its level is below the gate level **199.** However, signal **198** can be amplified to the amplitude of signal **200,** to reach above the gate level, and simultaneously the other lower frequency signals **197** can be attenuated to signal levels **201** by the use of differentiating operational amplifier **204** of FIG. **13.** The differentiated signals measured at output **213** are shown in FIG. **12B.**

In order to show the interconnections between amplifiers **79** and **204,** some components of FIG. **3** are repeated in FIG. **13.**

The operational amplifier **204** is a "voltage amplifier" (in contradistinction to the "current amplifier" **79**). It amplifies the output voltage of amplifier **79** by feeding it through capacitor **205** to the non-inverting input of amplifier **204.** The differentiating time constant is formed by capacitor **205** and resistor **206.** The input impedance (parallel to **206**) at the non-inverting input is very high, hence it has substantially no effect upon the resistance of resistor **206.**

The time constant shown in FIG. **12** is $.01 \times 10^{-6}$ farad $\times 100 \times 10^{3}$ ohms $= 10^{-3}$ seconds. The gain of amplifier **204** is defined by the ratio of resistors **207** and **208.** Resistor **212** being only 1 percent of the value of **208** (10 kilohms against 1 megohm) can be neglected. Hence, the gain is 1 megohm/100 kilohms = 10. In order to vary the gain of a large number of amplifiers such as **204** by a single control in the cabinet, the field effect transistor **209** forms part of a potential divider **212, 211.** When the field effect transistor is switched on by placing a positive potential via resistor **210** on its base, the very high impedance of the switched off field effect transistor becomes a fraction of the value of resistors **212** and **211** and only one-half of the output voltage is fed to resistor **208.** By this means the gain of amplifier **204** is raised to **20** from **10.** The gain of the differentiating amplifier is varied according to the inspection requirement by changing the potential divider **211, 212.** The output of the differential amplifier **204** is fed, via the diodes **214** and **215** (feeding positive and negative signals respectively) to the common interconnecting links of any large number of amplifiers **79,** as was described hereinbefore.

The low frequency amplifier outputs, as previously stated, are fed through large numbers of diodes **83, 84, 85,** etc. and **86, 87, 88,** etc. to the positive output terminal **90** and a negative output terminal (which was not drawn and numbered). The high frequency content of the signal processed through operational amplifiers **79,** further amplified by operational amplifiers **204,** is fed through identical diode gates (**214, 215,** etc.) to the same positive terminal **90** and negative terminal (not drawn and numbered).

The gate level **199** is set to satisfy the fixed gain of the low frequency amplifiers; the gain of the high frequency amplifier is set to operate with the already established gate level **199.**

Each amplifier **79** is best coupled with an amplifier **204.** While it is possible to use one differentiating amplifier **204** to process the output of several amplifiers **79** (feeding **204** from the common links cimbining said diodes **83, 86**), this would increase the signal-to-noise ratio because the combination or paralleling of low frequency noise can result in heterodyne effects and in a higher frequency content than the basic components.

Certain types of defects extended in the direction of the web-flow can only be detected reliably by the use of integration. This statement holds true for an inspection system wherein photosensor cells form a row in the cross-machine direction and which is only modulated by the movement of the sheet, the movement being at right angles to the cross-machine direction.

For example, such defects are a pencil line in the direction of flow, a crease, a coating line, or similar faint defects narrow in the cross-machine direction and extended in the flow direction.

The slit-like aperture can only see a fraction of said defects; however, the defect signal can be built up to the readout gate level by time integration.

In FIG. **14A,** signals **218** represent the steady noise signals present at the output of each of many amplifiers **79,** which are always below the voltage level **220.** Signals **219** which are higher than the steady noise peak level **220** are generated by a faint defect extending in the direction of flow.

As signal **219** is below the readout gate level **199,** it cannot be detected. However, using the integrator system consisting of a pair of operational amplifiers **228** and **241** and associated circuitry fed from several amplifiers **79** through diodes **83, 84, 85,** etc. and **86, 87, 88,** etc., as defined in FIG. **15,** signal **219** can be integrated above the readout gate level **199** as shown by signal **222** and simultaneously the steady noise signal **218** can be reduced to a substantially zero level.

The output of the integrating system then can be fed to eigher a separate differential acomparator type readout like **93** in FIG. **3** sensing negative excursions; or it can be fed via a coupling diode to the same readout of the differential comparator type which is also fed by diodes **86, 87, 88,** etc.

In order to process by integration both the positive and negative outputs of several amplifiers of the type **79,** the diodes **83,** etc., responding to a positive signal are fed direct to the input terminal **223** of the integrator system. The diodes **86,** etc., responding to a negative signal are fed to another input terminal **225** of the integrating system. The signals through terminal **225** are inverted by the use of a unity gain amplifier **241** and fed via combining diode **244** to the input **223** of the integrator amplifier proper **228.**

The unit gain of operational amplifier **241** (which conveniently is one-half of an operational amplifier pair type ML747 (two 1741) is obtained by the use of input resistor **242** and feedback resistor **243** having equal resistances. As the input DC level at terminal **223** is approximately +0.5 volt and as the coupling of the inverted amplifier is best done through gating diode **244,** in order to overcome the voltage drop in diode **244,** the output level of the inverting amplifier **241** is raised to approximately +1 volt by biasing the non-inverting input of amplifier **241** to approximately +0.5 volt with resistors **246** and **247.** For input offet compensation, resistor **247** has the same resistance as resistor **242,** and resistor **246** is connected to the +15 volt supply line.

By this means, the substantially equal noise amplitudes through the positive polarity diodes **83,** etc., and the negative polarity diodes **86,** etc., are brought to the same level when combined at input terminal **223.** The DC mean level of terminal **223** can be set by potential divider **248** and attenuating resistors **251** and **252** to any desired level: to zero level or a more positive level than 0.5 volts. By this means, the sensitivity of the integrator to respond to a low level signal is controlled. The integrator is made more sensitive to minute defect signals by adjusting the input voltage level closer to zero, and is made less sensitive when applying a more positive potential to terminal **223.** This control suppresses the noise and the defect signal. It also helps to separate the useful signal from the noise signal. Hence, potentiometer **248** is termed the noise sensitivity control.

It will be disclosed later that the more amplifiers are combined at terminal **223,** the smaller is the input noise level and the higher is the frequency content of such reduced noise level. (See FIGS. **17A** and **17B**). Such noise level at the input of the integrator can be zeroed, as was indicated in FIG. **14B,** by a "peak diode volt meter type input" formed by diodes **83, 84, 85,** etc., and **244,** and by capacitor **224** and resistor **226.** Any noise at terminal **223** will attenuate to zero or ground level at the junction of capacitor **224** and resistor **226** after a few seconds. The time of attenuation is governed by the time constant of capacitor **224** and resistor **226** which is, in the circuit of FIG. **15,** 4.7 seconds. Hence, it can be said that a steady signal at the input of the integrator system will become zero after approximately 5 seconds.

Any abnormal signal which is above the steady peak-to-peak levels of the combined noise signals of all the amplifiers feeding the integrators, such as signal **219,** is then integrated according to the integrating time constant formed by input resistor **227** and one of capacitors **229.** One of **11** capacitors **229** is selected by the integrator sensitively switch **230.** The sensitivity of integration is the greatest when the smallest of capacitors **229** is switched from the output **234** of amplifier **228** to its inverting input. Th integration sensitivity is less when a larger capacitor is used in the feedback path. By using a series of capacitors, 100*pf*, 200*pf*, 300*pf*, 470*pf*, 620*pf*, 910*pf*, 1,500*pf*, 2,200*pf*, 3,300*pf*, 6,600*pf*, and .02 microfarad, the integration sensitivity is changed in approximately 60 percent steps and covers in practice efficient integration from a fraction of an inch to many inches of web travel, at web speeds from 10 feet per minute to thousands of feet per minute. Integration is a function of web speed. Integration sensitivity setting can be calculated for any operational web speed. Alternatively, resistor **227** can be varied automatically proportionately to the web speed.

It will be noted that the integrated output signal **232** in FIG. **15** reaches the saturation level of the amplifier at approximately minus 12 volts and its stays there. As long as signal **232** is above the gate level the system will show a continuous defect, even after the disappearance of the defective section. Hence, the integrators have to be reset or zeroed periodically (**233** in FIG. **15**). This is done by resetting pulses **274** generated in the circuit of FIG. **16.**

(In FIG. **14B**, signal **222** is shown in opposite phase to the actual output **232.** It is easier to explain integration by not inverting the signal polarities in FIGS. **14A** and **14B.**)

The integration can be switched off by switch **230** when a feedback resistor **231** is connected in this feedback path; then the gain of amplifier **228** is a fraction of unity.

In order to keep the voltage level of integrator output **234** near ground level during the integrator resetting pulses and when the input is zero, diode **235** responding only to positive excursions, forms a feedback path through resistor **236**; for positive excursions, the gain is less than unity. The integrator resetting pulses **274** are fed through terminal **240,** current limiting resistor **239** and through diodes **238,** to the inverter input. As will be seen from the description of the integrator resetting pulse generator in FIG. **16,** terminal **240,** and hence the cathode of diode **238,** is biased to approximately +1.2 volts. Hence to approximately a +1 volt level at the integrator input, diode **238** presents a very high impedance and has no effect upon the linearity of integration. The voltage level of the inverter input during the integration process is substantially at ground level. Hence, the biased diode **238** is an effective gate which is open only during the duration of the integrator resetting pulses which reach a negative peak potential of approximately − 2 volts.

Integrating in any desired sheet area, changes in the noise signal elevels, i.e., variations which are above the steady rectified peak-to-peak noise signal generated by the unblemished sheet material with standard formation and surface finish an exact measure can be obtained for abnormal finish. For example, each 10 × 8" sheet area could be integrated by the circuit of FIGS. **15** and **16**: feeding the outputs of 16 amplifiers **79,** i.e., the outputs of two standard 5 inch wide unit-head-sections to one integrator and resetting the integration for every 8 inches of sheet travel.

Or the whole signal intelligence, say, of a fine crease, many inches long in the direction of flow, can be truly integrated by this means, giving a defect amplitude which is proportional to the products of the crease length, crease width and its intensity (apparent contrast against normal background).

A remarkable feature of the combination of the noise signals of many amplifiers is the amplitude reduction of the combined noise. When the peak-to-peak amplitudes of rectified noise signals, which exhibit the same character, frequency content and peak levels, are combined through diode gates, such as **83, 84, 85,** etc., **86, 87, 88,** etc., and diode **244,** the resultant noise amplitude at the input of the integrator **228** is reduced even when measured at the junction of capacitor **224** and terminal **223** and its frequency content and uniformity increased. Indeed, by combining a very large number of noise signals of substantially equal peak-to-peak amplitudes, the resultant signal at the input terminal **223** is pure DC - which results in a zero level (after approx. 5 seconds) at the operational amplifier side of capacitor **224,** meaning that a uniform web without flutter does not affect the integrators, which then responds only to abnormal finish and defectiveness.

The integrators resetting pulse generator with pulse repetition rates F from 1 to 1,300 pulses per second is defined by FIG. **16.**

A calibrated dial attached to potentiometer **255** calibrated by **40** scale divisions from 1 to 4 (in decimal fractions) associated with range switch **254** and calibrated by adjustable resistors **256** and **259** define the pulse repetition rate and pulse duration of the integrator resetting pulses **274** appearing at the output terminal **268.**

A saw-tooth waveform **271** is generated by charging capacitors **254** through resistors **255, 256, 257, 258** also connected to the control base of unijunction transistor **252.** The current through unijunction transistor **252** is controlled by resistors **259** and **260.** The generation of the saw-tooth signal **271** is also defined by resistor **261.** The low current and (set 1) of the potentiometer **255** is best adjusted by variable resistor **256.** The high current end (set 4) is best adjusted by variable resistance **259.**

Associated pulse waveforms **272** and **273** clarify the function of the circuit components. The pulses **272** generated at the unijunction transistor are fed through potential divider **263** and **264** to emitter follower **266.** The use of three-series connected diodes **265** establish a positive 1.8 volt level for the base of emitter follower **266** and a corresponding level of +1.2 volts at the output terminal **268** of the generator. Transistor **266** has sufficient power to reset a large number of integrators of the type defined by FIG. **15.**

As was already stated, the standard amplifiers **79** (built into the unit-head-sections) have a sensitivity of 1 volt per microampere. When the change of current in a photosensor caused by a blemish is less than 1 microampere, further amplification is required; eg., when looking for small defects with limited contrast changes on dark or coloured surfaces.

Such further amplification can be accomplished by one only amplifier shown in FIG. **18.** The output of a large number of amplifiers **79** can be processed by operational amplifier **285.** Again, by combining many outputs of amplifiers **79** through positive diode gates **83,** etc., and negative diode gates **86,** etc., the signal-to-noise ratio can be increased considerably. Therefore as long as the defect-signal reached a voltage level at the output of **79** of, say, **50** millivolts, a level which is an order of magnitude greater than the DC voltages level variations present at the outputs (junction of resistor **78** and diodes **83, 86** in FIG. **3**) of the amplifiers **79,** the use of the circuit of FIG. **18** practically eliminates the noise content and raises the useful signal to the desired readout level.

Without the use of input offset current and voltage correction, the output DC levels of amplifiers **79** are only a few millivolts relative to ground or zero potential.

The noise signal reduction at the input is shown by FIGS. **17A** and **17B.** Three noise signals **275, 276** and **277** combine to resultant **278,** the peak-to-peak amplitude of which **281,** is much a smaller than amplitude **279** or the rectified amplitude **280.** Resultant **278** is formed after the positive diodes **83, 84** and **85** at terminal **90.** When the negative parts of noise signals **275, 276** and **277** are rectified by diode gates **86, 87** and **88,** inverted in operational amplifier **241** (identical inverter to that used in FIG. **15**) and combined at terminal **90,** the resultant noise signal is further reduced to a maximum peak-to-peak level **283.** The deepest "gaps" of signal **278** are filled in by inverted signal peaks **284.**

It should be noted the noise signals **275, 276** and **277** were arbitrarily drawn.

Operational amplifier **285** amplifies the resultant signal of FIG. **17B** in four steps defined by resistors **290, 291, 292, 293** and **294.** Field effect transistors **286** and **287** are electronic switches; when a positive potential (+ 15 volts) is applied through resistors **288, 289** to their base, the transistors present a resistance of a few hundred ohms and act like shorting links across resistors **290,** or **294.** The approximate steps in amplification are: 1 (**286** off, **287** on), 2 (**286** off, **287** off), 5 (**286** on, **287** on, and 15 (**286** on, **287** off).

The approximate +0.5 volt DC offset voltage at the input of amplifier **285** is compensated by balancing potential divider network **295** such that the DC level at terminal **296** is set to zero. As resistor **290** is switched on and off during gain change adjustments, affecting the input offset voltage, balancing potentiometer **295** has to be also reset. The checkout and control oscilloscope of an inspection system is normally connected to terminal **296,** hence the output voltage levels are automatically monitored.

Re-balancing of amplifier **285** is not required when the gain change is controlled only by changes in the feedback path **293, 294** to which several switchable resistors can be added, or when feeding back via an adjustable potential divider connected between terminal **296** and ground.

When one only amplifier **285** is used for a system, latter gain control is preferred. When, however, several amplifiers of the **285** type have to process several independent readouts, i.e., on wide sectionalized machines, the electronic switching alternative is preferred, because then it is possible to set by one switch control (gain) and a switched potential divider (gate level for readouts) the widest of inspection machines.

When the DC light level falling on a phototransistor of, say, the FPT-100 type, results in a photocurrent of only a few microamperes, the high frequency response suffers. For example, when the light modulation in the

circuit of FIG. 19A was measured as **230** millivolts, that is corresponding to a cell modulation current change of 0.23 microamperes, when the DC light level gave 2 microamperes cell current: the rise time was measured at 150 microseconds and the peak-to-peak noise level at 10 millivolts (0.010 microampere).

As was shown, the rise time of the defect signal measured between zero and the readout gate level for the defect signal should be 50 microseconds or less in some inspection applications. By connecting at least a 1 megohm base resistance to a potential, resistors **297, 298** and **299,** such that the DC cell current is set to **25** microamperes, the high frequency response is considerably improved. Test results gave for the identical light modulation as was described above, a rise time of 20 microseconds. The noise level was slightly increased to 20 millivolts.

For the circuit of FIG. **19**A the exact identity of combined cell sensitivity and amplification and constant noise level is obtained for many cells and amplifiers by using an adjustable feedback resistor chain **300** and **301.**

The equivalent circuit of FIG. **19**A is shown in FIG. **19**B. The high impedance current generator **303** corresponds to the photodiode which has a common collector with the transistor. The base resistance orb is approximately 200,000 ohms; the emitter resistance is negligible; hence when the base biasing resistor **299** (RB) is less than 1 megohm a significant part of the diode current can leak away. Therefore, the biasing resistor **299** is made at least 1 megohm.

The main influence of the phototransistor upon the amplifier **79** performance is an apparent capacity **302** which is estimated to be approximately 1,000 picofarad. The elimination of ringing and the simultaneous increase of the rise time of the system when introducing the coupling resistor **70** can be understood with the aid of the equivalent circuit of FIG. **19**B.

By way of an example, an inspection system, for a 40 inch wide web, is shown in FIG. **20** in which many features of the invention are combined. It consists of a standard head system used for substantially all types of defects, an oscillating head for the detection of fine lines and scratches extended in the direction of flow, standard constant gain amplifiers **79** and the differentiating amplifiers **204** housed within the heads, diode logic combining the outputs of all amplifiers, the so combined positive and negative polarity defect signals lead through two wires only (in the cable connecting the inspection heads with the control cabinet) to the control system, which consists of a long time constant amplifier **285** with adjustable main control **304,** an integrator **228** with adjustable sensitivity control **229,** an integrator resetting pulse generator with pulse frequency **254** and pulse frequency range controls **255,** a two-stage differential comparator **93, 306,** with gate voltage level adjusting switch **305,** control **307** to change the gain of the differentiating amplifiers **204,** and a potentiometer control **313** to adjust the intensity of the lamps used for illuminating the oscillating head.

As the material is opaque, it is illuminated only from the viewed side with constant intensity (no control required following initial setting).

Eight unit-head-sections are used for the 40 inch web width containing $8 \times 16 = 128$ phototransistors **64.** In order to detect all types of defects, each pair of phototransistors feeds a long time constant, constant gain amplifier **79.** There are 64 such amplifiers. Only **4** are shown in FIG. **20.** In order to detect minute defects and suppress the non-uniformity of coating and surface formation, the outputs of amplifiers **79** are further amplified by 64 differentiating amplifiers **204.** The adjustable gain of amplifiers **204** is switched by a single control **307** in the control cabinet.

In order to detect the finest scratches and coating lines in the direction of web flow, an oscillating head with apertures parallel to the web flow is added to the system as a refinement. Each phototransistor **64** is amplified by a constant gain standard amplifier **79** with a short time constant. There are 64 such amplifiers.

Hence, the total of $3 \times 64 = 192$ amplifiers are combined with diode gates **83, 86, 214, 215,** at two only output junctions **216, 217** which in turn are connected by cable to the control cabinet.

The system is set by seven controls which are adjusted with the aid of an oscilloscope connected to test points **310** and **311.** The output of differential comparator **306,** that is the outputs of the system, can be fed to a number of readout stations such as a reject control computer, a marker control computer, to counters, to a defect size selector which may be associated with a further counter for counting defects greater than a selected size, to Summers or electronic counters which can define the total defectiveness or the number of defects in a selected sheet area.

I claim:

1. Apparatus for detecting blemishes in sheet material arranged to flow past an inspection head of the apparatus, the apparatus comprising light source means arranged to direct light onto the sheet material, a plurality of photosensitive devices arranged in the inspection head in a line transverse to the direction of flow of the sheet material so that the photo-sensitive devices receive light transmitted through or reflected from respective adjacent portions of the sheet material as it passes the photo-sensitive devices, each device being adapted to generate an electrical signal dependent on the intensity of light received by the device, and a circuit for deriving a common output signal from a plurality of amplifiers each adapted to generate in response to an input signal individual to the amplifier an electrical output signal including a random noise signal, the circuit comprising a plurality of rectifiers each having one terminal adapted to be connected to the output terminal of one of the amplifiers and its other terminal connected to a common output terminal, and means for biasing the rectifiers so that, in use, the random noise signals from the amplifiers are combined at the common output terminal to produce a resultant noise signal having an amplitude less than those of the individual noise signals, each of the amplifiers of the circuit being arranged to receive as an input the electrical signal generated by one or more of the photosensitive devices.

2. Apparatus as claimed in claim **1,** in which the inspection head comprises a housing on which are mounted a plurality of the photo-sensitive devices and a separately formed, replaceable collimating member having an aperture through which, in operation, light transmitted through or reflected from the sheet passes, to fall onto the photo-sensitive devices, the collimating member being detachably fixed to the housing.

3. Apparatus as claimed in claim 2, in which the inspection head comprises a plurality of housings formed by a corresponding number of separate head sections, each head section being detachably mounted on a common support member extending transversely of the direction of flow of sheet material through the apparatus.

4. Apparatus as claimed in claim 3, in which the support member is hinged to a main frame of the apparatus, to enable the inspection head to be moved from an operative position in which the aperture of each collimating member is close to the path of travel of sheet material.

5. Apparatus as claimed in claim 2, in which the or each housing is in the form of an airtight case, and means are provided for supplying dust-free air under pressure to the housing, the air leaving the housing through the apertures in the collimating members.

6. Apparatus as claimed in claim 1, in which adjustment means are provided for adjusting the distance between the apertures of the collimating members and the path of travel of the sheet material.

7. Apparatus as claimed in claim 1, in which there are provided support means providing a support surface for supporting sheet material as it passes the inspection head, the support means being adjustable to enable the support surface to be made selectively convex, flat or concave.

8. Apparatus as claimed in claim 2, in which the or each collimating member comprises two side walls converging towards the path of the sheet material, the aperture being defined between flat faces formed at adjacent ends of the side walls and parallel to the plane of symmetry of the collimating member.

9. Apparatus as claimed in claim 8, in which the or each collimating member is divided by ribs extending between the side walls into sections each corresponding to one of the photo-sensitive devices.

10. Apparatus as claimed in claim 2, in which the or each collimating member comprises two side walls converging towards the path of the sheet material, the adjacent ends of the side walls being cut off in a plane parallel to the plane of movement of the sheet past the members, the aperture being defined by the adjacent edges of the inner surfaces of the side walls.

11. Apparatus as claimed in claim 2, in which the or each collimating member comprises a slit of adjustable width positioned between the photo-sensitive devices and the path of sheet material, and the light source means comprises lamps positioned at a comparatively large distance from the path of the sheet at the side of the path remote from the photo-sensitive devices, so that substantially parallel beams of light transmitted through sheet material in the path pass through the slit onto the photo-sensitive devices.

12. Apparatus as claimed in claim 2, in which the or each collimating member includes fibre-optics means arranged to conduct light reflected or transmitted from the sheet material to the photo-sensitive devices.

13. Apparatus as claimed in claim 12, in which fibre-optics means is provided to conduct light from the light source means to the sheet material.

14. Apparatus as claimed in claim 1, in which the photo-sensitive devices are adapted to respond to infrared radiation, and infrared filters are disposed between the light source means and the sheet material.

15. Apparatus as claimed in claim 1, in which the or each collimating member includes an aperture adapted to be oscillated in a direction transverse to the path of sheet material and parallel to the plane of the sheet as it passes the apertures, to detect line defects of the sheet extending in the direction of flow of the sheet.

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