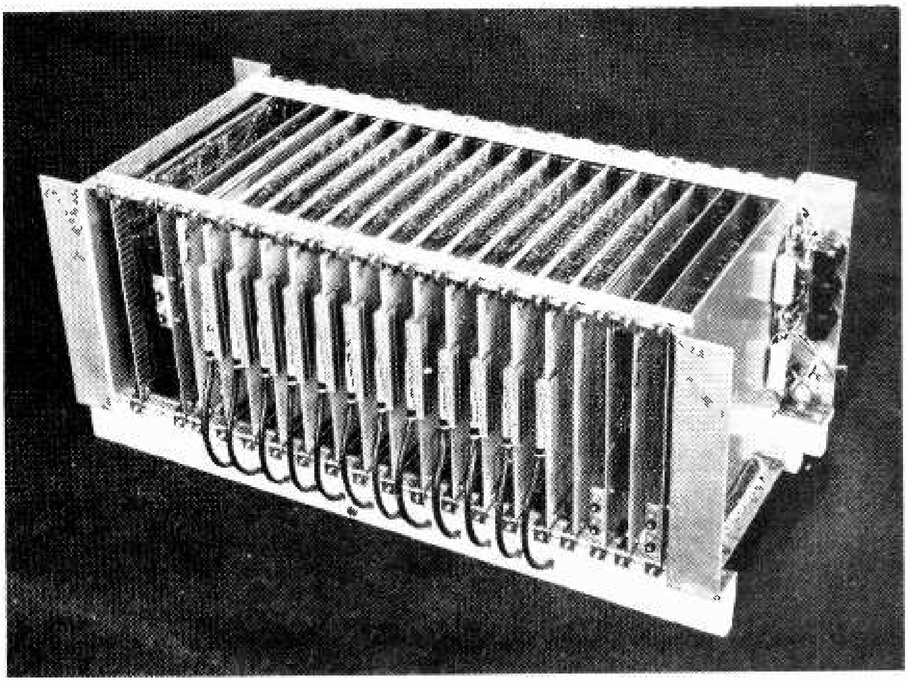
Electronic organ tone system

Modular design uses sine wave synthesis to produce a high quality pipe organ sound

by A. D. Ryder, M.A., Ph.D., F.I.E.E.

ALTHOUGH ORGANS take many forms, the pipe organ is generally the standard by which others are judged. The main role of electronics is to provide an acceptable replica of a pipe organ at a fraction of the cost. This electronic organ tone system design differs from many commercial instruments by using a harmonic-synthesis approach. It provides for a full-size two-manual organ with 61 keys on each manual, and 32 on the pedals, which may be played polyphonically. Several variations and additions are possible including comprehensive coupling. Keying is by d.c., and only one contact per key is needed. The design is suitable for modernising an existing instrument or for a new console. Shorter keyboards may of course be used, with some saving in components. The pedal department is based on a 16ft pitch and the manual departments are on an 8ft pitch. Apart from a multiple frequency-divider, all components are general purpose types, and the basic system is condensed onto 19 boards which can be housed in a standard 17in rack. Component cost for the basic system is around £450 and optional coupling circuits add about £65.

Fig. 1. *Assembled system in a 17in rack. The illustration does not show the mains transformer which is mounted separately. Twelve connectors are used to bring in the key signals to the front of the gate cards.*



Introduction

If the playing tones for an electronic organ are to be derived from a common source, rather than from individual oscillators, there are two main methods of producing the different waveforms required for stops of different tone colours. A harmonically rich waveform, such as a sawtooth, may be selectively filtered, or individual harmonics as sine waves, may be combined in different proportions. A practical substitute for a sawtooth is the staircase waveform obtained by mixing square waves in octave pitches, thus filling in the even harmonics, and this method is currently popular because square waves are easily generated and manipulated. The second method, known as sine wave addition, was used in the original Compton and Hammond designs based on electro-mechanical generators. In principle, any required waveform can be produced by either method, but in practice there is a significant difference because of the frequency range needed for a four or five octave keyboard. If a sawtooth of constant amplitude is fed to a filter, the output will vary with frequency, in both waveform and amplitude. However, with the sine-addition method, in its simplest form, these factors remain constant. Neither of these is ideal, but the second is closer to a pipe organ stop. Variations in tone-colour and loudness often represent the main restriction of an instrument which uses subtractive filtering. The sine wave addition technique was primarily adopted because the problems of achieving a musically satisfactory result by the filter method appeared very considerable.

In the basic system, seven sine wave pitches of ratios 1, 2, 3, 4, 5, 6 and 8 are provided for each manual and for the pedal, the pedal pitches being set an octave lower, starting at 32.7Hz. Different stops or tone-colours are directly produced by different combinations of harmonics. The harmonic spectrum can be widened by coupling, or by providing additional waveforms. There is a total of 154 keys, and, although the harmonics do not extend beyond about 10kHz, there are more than seven tone-gates per key if provision is made for upward coupling. Much of the design effort has been directed to minimising the space required, and the complexity of interconnection for the large number of gates.

Frequency generation

All of the frequencies are derived from one master frequency of about 1MHz, which is controlled by a crystal with a variable offset. This gives approximately 1% tuning above and below standard pitch so that the organ may be tuned to another instrument. The master frequency is fed to a multiple divider which provides 12 reference frequencies closely approximating an equal-tempered scale. All of the playing frequencies, 300 in all, are derived from these references. The use of a common frequency source is practically convenient and economical, but it cannot give the effect of different ranks of pipes, slightly out of tune, sounding together as a chorus. This effect is most closely reproduced by instruments which use a separate oscillator for each note of each stop. However, the present design does allow for a "quasi-chorus" effect, which is described later. The playing frequencies are generated and gated as square waves which are then filtered into sine waves with approximately 4% harmonic content. The filtering takes place before the mixing process, and does not affect balance.

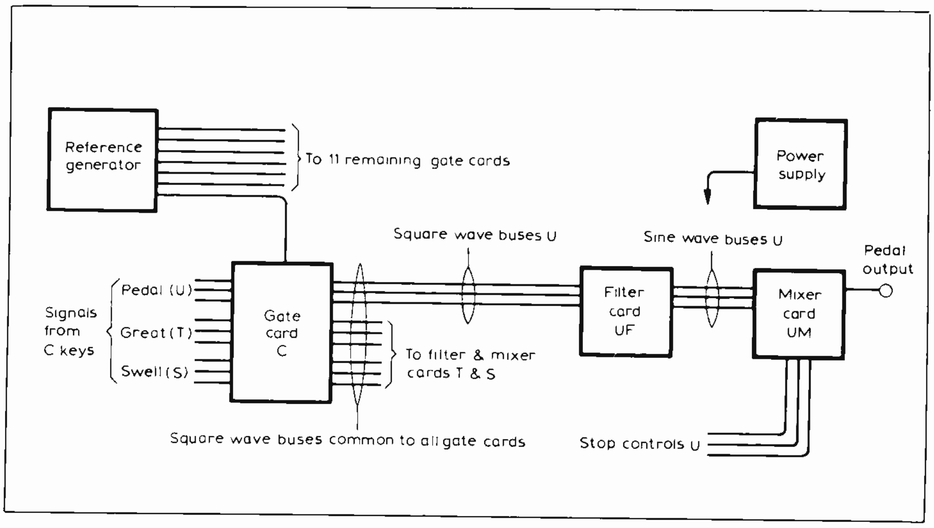


Fig. 2. *Block diagram of basic system which comprises 12 gate cards, 3 filter cards, and 3 mixer cards. If the coupling circuits are used they are interposed between the key signals and the gate cards.*

Voicing and regulation

In organ terminology, voicing is the adjustment of the sound quality of a pipe, and regulation is the adjustment of loudness. Each pipe is adjusted to build up the stop of which it forms part. In the most advanced sine wave organs, complex wiring and mixing circuits allow the amplitude of each harmonic to be independently adjustable note by note for each stop, so that voicing and regulation are similar to a pipe organ. In the present design, there is only one signal line for each harmonic pitch of each keyboard, so that each harmonic combination can easily be set up, but has to suffice for the whole keyboard. As already mentioned, a constant amplitude is not satisfactory, therefore each harmonic is independently pre-regulated by choosing appropriate resistor values. The level is set, note by note, to give an aurally satisfactory balance over the frequency range. With this method, combinations of harmonics also tend to be balanced and free from major variations of loudness or tone quality. It is possible to vary the relative strength of any chosen harmonic for different notes by using RC combinations at the mixing stage so that the built-in regulation can be modified for better voicing of a particular stop.

Harmonic accuracy

In some older sine wave organs, harmonics were borrowed from higher notes. For example, the 3rd harmonic for C1 (note C of the lowest octave) would be taken from the generator for G2, the 5th harmonic from E3, and so on. Apart from the octaves, the equal tempered scale does not provide true harmonics. The frequency of G2 is close to 3 × C1, but E3 differs by nearly 1% from 5 × C1. An error such as that of E3 would probably produce a rough tone, but a more serious objection to borrowing is that it detracts from the richness of chord sounds by eliminating some of the frequencies which should be present. In the present design each harmonic is generated in relation to its own fundamental from the same reference.

Starting transients

An organ pipe may take a few tens of ms to speak fully, and some types sound harmonics before the fundamental. To simulate such pipes it is necessary to control the build-up of each harmonic independently, note by note. In a sine wave system this is not difficult, but requires a number of keying circuits which are individually adjusted for each stop.

This design uses a common keying circuit for all harmonics together. The attack is graded so that, within limits, high notes speak faster than low notes.

Coupling

Coupling is not very common in electronic organs and, if offered, may be limited and expensive. In pipe organs however, coupling is nearly always used to connect more pipes to each key. This can enhance the sound and extend the variety of registration (combination of stops) available. Couplers may be local or interdepartmental. The action of the first kind is to couple each key to a higher or lower note of the same keyboard. The most common is an octave coupler, which causes key CK1 to sound C2 as well as C1, DK1 to sound D2 and D1, and so on. Others are the sub-octave, and the super-octave which is two octaves higher. A drawback of local coupling is the missing notes. If, for example, CK1 is pressed there is the addition of C3 but no more sound at C2 level.

The most common interdepartmental coupler is the great-to-pedal, which makes the great manual playable from the pedals and simultaneously with any stops drawn on the pedal organ. This coupler works only one way so that the pedal department is not connected to the great manual. Usually, a full set of upward couplers is available which, for a two-manual organ, would consist of great-to-pedal, swell-to-pedal, and swell-to-great. Couplings such as swell octave-to-pedal are also used as well as a unison-off coupler, actually an un-coupler, which allows the octave, or a coupled department, to be sounded alone.

For an electronic organ, couplers offer similar advantages. In a sine wave instrument, coupling the octave and/or the twelfth locally or from another department, also provides a means of broadening the harmonic spectrum. Although the present design can be used without couplers, suitable circuits will be described which can be added to the basic system. For coupling purposes, the manual departments each have 68 keying inputs, extending up to GK6, and the pedal has 44, up to GK4. The swell-octave provides the pedal with stops at a 4ft pitch, i.e. two octaves above normal.

A special feature is that the relative strength of the coupled note, or of the unison, may be adjusted so that, for example, the degree of brilliance added by the octave may be varied. Also, if the octave is used at reduced strength, the missing note effect is mitigated because when the octave key is played it makes an additional contribution at its own pitch level.

Other options

The coupling system and the quasi-chorus effect are options particularly associated with this design, but other additions are possible and some practical circuits will be described. Arrangements for volume control are optional but, if orthodox practice is followed, only the swell department will be controlled by the swell pedal and the loudness of the other departments will be determined by the selection of stops provided. To avoid electrical noise the volume pedals should work on d.c.,

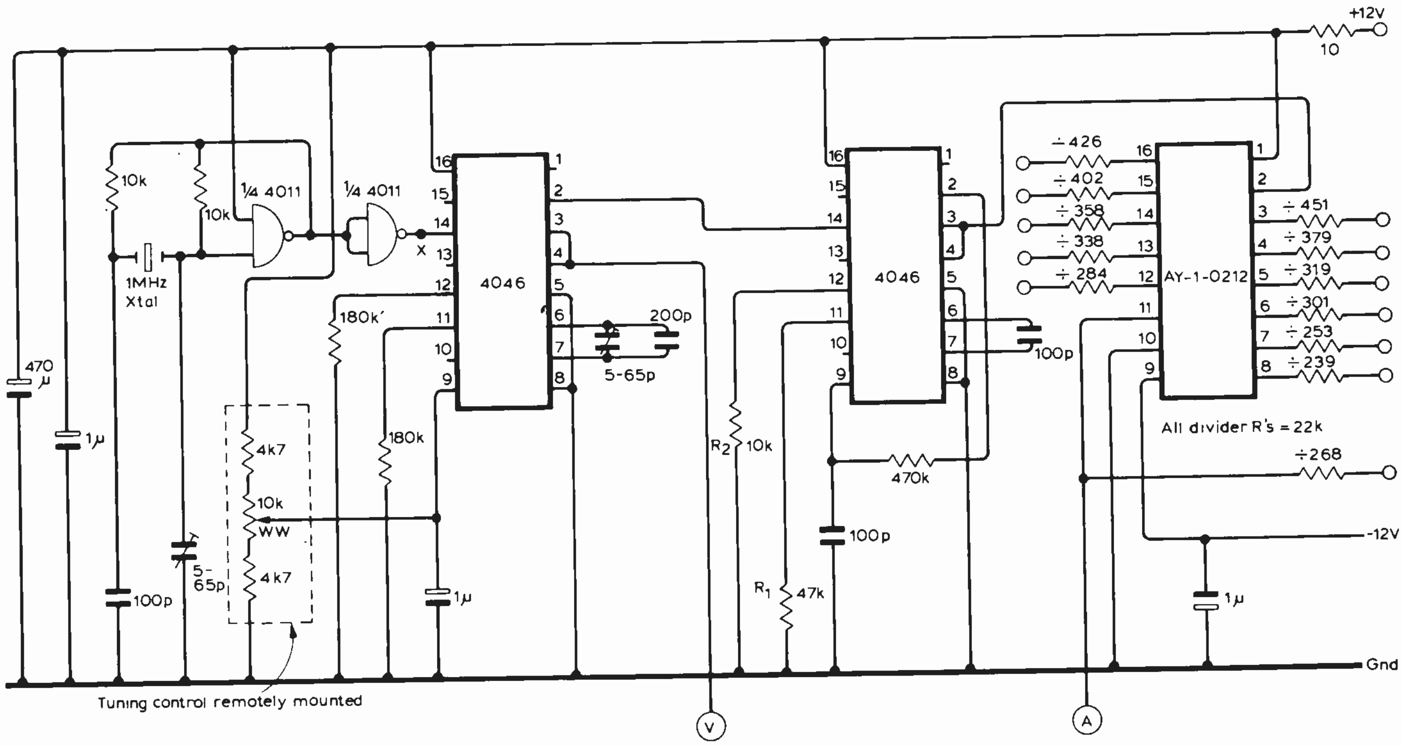
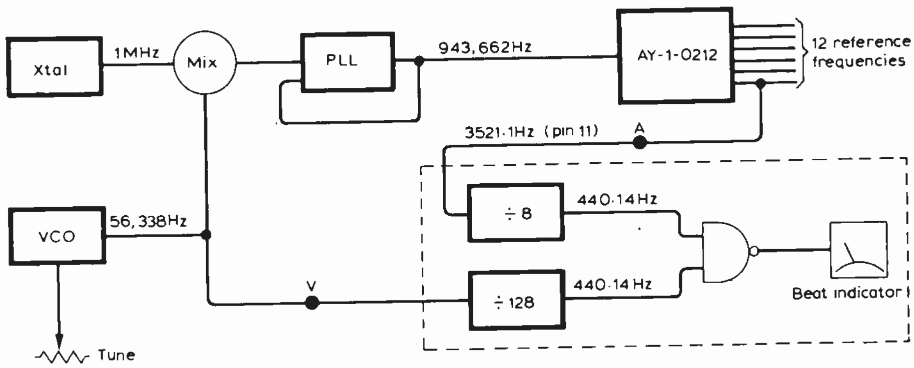


Fig. 4. *Tunable reference generator circuit. The 2k2Ω and 4k7Ω resistors, R_1 and R_2 should be 2%. For fixed tuning the two 4046 i.cs and associated components are omitted and the 1MHz signal at point X is taken directly to pin 2 of the AY-1-0212.*



rather than directly on the signal. Vibrato, frequency-modulation, may be applied to the generators to affect all departments together or, by using an external modulated delay device, to an individual department. Tremulant, amplitude-modulation, may be applied selectively to a single department. Chiff, starting transients, can be introduced but are restricted because all of the harmonics are keyed together. A noise busbar can be provided for adding to stop mixtures of each department. The keying envelope can be given a long decay, sustain, which can be graded over the keyboard, but the inherent attack rate is not fast enough to simulate a piano sound.

In pipe organ practice, pistons or press-buttons are often provided to bring in pre-selected stop combinations. This facility can be achieved using a c.m.o.s. memory.

Although it is not intended to deal with power amplifiers, an electronic organ provides a fairly severe test for loudspeakers, therefore a suggested design using an active crossover will be described. The ability to regulate each harmonic independently allows compensation for irregularities in loudspeaker response and this is especially useful in the region below 100Hz.

Mechanical description

To reduce interconnections, the circuits are assembled on plug-in cards which ease construction, testing and setting-up. The printed circuit boards are the same size as general purpose boards on the market so that both types can be used in the same assembly. Edge connections are mainly straight buses, and a motherboard is not necessary. The card size of 8in × 6½in can accept 59 edge connections at 0.1in spacing, and in the basic form the design uses 19 cards of four types. Gate cards; these are specially designed and 12 are required. Filter cards; also specially designed, one per department. Mixing cards; one per department, constructed using plug-in Veroboard. Oscillator card; assembled on one plug-in Veroboard, with some space for additional circuits. The photograph in Fig. 1 shows the rack containing the basic system. There is space for a 20th card which can be used for further options. The power supply components are mounted on one of the side panels, and the mains transformer is mounted separately. Due to space limitation the coupling circuits cannot fit into the main rack, but can be assembled on a large Veroboard mounted horizontally below. It is possible to add a second set of cards to provide three more independent departments which could be coupled to the keyboards and would allow a third manual to be used. The harmonic range can be extended, and there are possibilities for independent treatment of keying and differential tuning. The descriptions to follow will show how the elements of the system may be adapted to meet various requirements.

Fig. 3. *Tunable reference generator system for providing frequencies shown in lower part of table 2. The standardising circuit in the dotted area has frequencies shown for zero beat. This circuit may be omitted.*

Circuit nomenclature

The octaves of each keyboard are numbered from the bottom so that the lowest key is CK1 and the next is C'K1, followed by DK1, D'K1 and so on up to BK1. The next octave starts at CK2. Apostrophes are used for sharp signs. On a 61-note manual, the highest key is CK6, starting the sixth octave, and on a 32-note pedalboard, the highest is GK3, about halfway up the third octave. The fundamental frequencies for the manual departments range from C 65.4 to C 2,093Hz, and from C 32.7 to G 196Hz for the pedal. For the notes C and their harmonics, there are six keying signals from each manual and three from the pedals, but for other notes there are fewer. The gate card design provides 16 keying inputs for use with couplers as previously described. The three departments are called pedal — U, great — T, and swell — S, so on any gate card the keying inputs run from UK1 to UK4, TK1 to TK6, and SK1 to SK6. On cards G' to B, the highest numbers are not used, so they have 13 inputs only.

The length of an open organ pipe sounding note C at 65.4Hz is about 8ft, and a pipe sounding twice this frequency is about 4ft and so on. Table 1 shows some of the lengths, intervals and typical names used. Descriptions in the text will use harmonic numbers unless otherwise stated.

Table 1

Harmonic No.	Footage	Interval	Typical name
1	8	—	Principal
1½	5⅓	5th	Quint
2	4	(8th)	Octave
3	2⅔	12th	Nazard
4	2	15th	Fifteenth
5	1⅗	17th	Tierce
6	1⅓	19th	Larigot
7	1 1/7	Flat 21st	Septime
8	1	22nd	Used in
10	4/5	24th	mixtures,
12	⅔	26th	also higher
16	½	29th	pitches

Pedal pitches are usually set an octave lower, starting at 16ft. The quint is not a harmonic but, if used with the fundamental, it can produce a sub-octave effect due to the subjective difference tone. Each pipe has its own spectrum of harmonics in addition to the pitch sounded.

Table 3. Frequencies relating to Fig. 3 for a tuning range of 1% either side of a zero beat frequency.

Deviation	Divider input kHz	V.c.o. output kHz	Beat frequency Hz
+1.0%	953.1	46.9	78.1
+0.8%	951.2	48.8	62.5
+0.6%	949.3	50.7	46.8
+0.4%	947.4	52.6	31.3
+0.2%	945.5	54.5	15.6
0	943.7	56.3	0
−0.2%	941.8	58.2	15.6
−0.4%	939.9	60.1	31.3
−0.6%	938.0	62.0	46.8
−0.8%	936.1	63.9	62.5
−1.0%	934.2	65.8	78.1

Table 2. Two possible sequences of reference frequencies from the divider.

	Input frequency 1MHz												
Pin	—	3	16	15	4	14	13	5	6	12	11	7	8
Note	C	C'	D	D'	E	F	F'	G	G'	A	A'	B	C
Hz	2093	2218	2350	2490	2637	2794	2960	3136	3322	3520	3729	3951	4186
Pin	3	16	15	4	14	13	5	6	12	11	7	8	—
	Input frequency 943.7kHz												

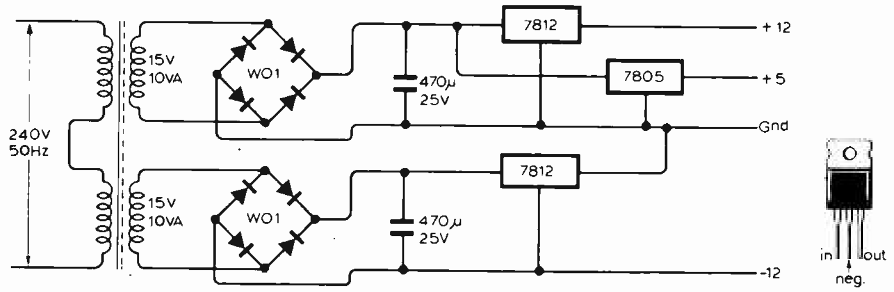


Fig. 5. *Power supply.*

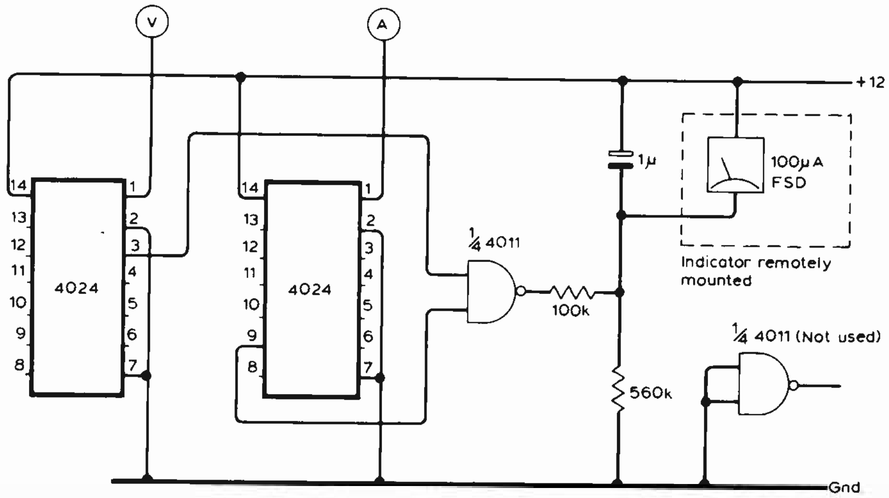


Fig. 6. *Tuning standardising circuit. The two resistors can be altered to suit different meter movements.*

Circuit description

A block diagram is show in Fig. 2. The 25 or so frequencies generated on each gate card have their mean values tied to the one incoming reference, but the complete card may be frequency-modulated independently of the reference. The locally generated frequencies are selectively switched onto the outgoing square-wave buses under control of the key signals via a keying matrix. For example, depressing CK1 on the great, assuming the unison coupler is on, will cause the C card to output 65.4Hz on the T1 square-wave bus, twice this frequency on the T2 bus, and so on. The three sets of buses are shared by all 12 gate cards, though each uses a different reference, and is wired to different keys.

Each departmental set of square-wave buses connects to a filter card which feeds a group of sine-wave buses to the mixer for that department. The mixer card carries a virtual earth mixing amplifier and switching circuits for connecting different combinations of harmonics to the mixer. The strength of each harmonic, and thus tone-colour and loudness of each combination or stop, is determined by a resistor or an RC circuit as already mentioned.

An octave adjustment by wire link is provided on the gate cards to allow some freedom in the design of the reference generator. The G.I.M. AY-1-

0212 divider gives 12 whole-number divisions of its input frequency in the ratio of $^{12}\sqrt{2}$, about 1.059, which is that required for an equal-tempered chromatic scale. As shown in table 2, if the input is 1MHz, the outputs range from C' 2218Hz to C 4186Hz, and if the input is a semitone lower at 943.7kHz, the outputs range from C 2093 to B 3915Hz. Appropriate routing of the outputs and the octave adjustments allows either frequency to be used or a number of others.

A tunable reference generator system is shown in Fig. 3. The frequency at one semitone below 1MHz is derived using a v.c.o. together with a mixer, and is recovered by a p.l.l. Instability of the v.c.o. has only a second-order effect, and it allows a ±1% tuning range for adjusting the organ to another instrument. The tuning control may be scaled with a frequency counter at the p.11. output, and table 3 shows the relevant frequencies.

At various points in the tuning range there will be a more or less simple whole-number ratio between the v.c.o. output frequency and its difference from 1MHz. The system in Fig. 3 exploits a convenient numerical coincidence and allows the tuning to be set up precisely to the crystal. Pin 11 of the divider, shown as the A reference, gives 1/268 of its input frequency, and this is the same as 1/16 of the v.c.o. frequency when the deviation from standard pitch (A is 440Hz, A reference is 3520Hz) is only +0.03%. This condition can be detected using a visual beat indicator as shown. The sensitivity, as table 3 indicates, is about 0.8Hz beat rate for 0.01% deviation. Because of the whole-number divisions, the AY-1-0212 can produce a theoretically correct frequency on only one output at a time, but if the pin 11 output is set 0.03% high, all outputs will be within 0.1%, which is sufficient for most purposes.

The circuit in Fig. 4 uses c.m.o.s. devices so the inputs of unused sections should be connected to a supply rail. The 10MΩ resistor sets the d.c. working point, the 10kΩ resistor gives some control of loop gain, and the trimmer capacitor allows some frequency adjustment. The first 4046 p.l.l. is not used in a loop, but forms the v.c.o. and mixer. Mixing is achieved by using the pin 2 phase comparator of the i.c. which exclusively-ORs its v.c.o. signal output with the 1MHz signal at point X. An output is generated at the difference frequency along with other frequencies. The v.c.o. frequency is controlled by the voltage at pin 9, and the working range is set by two 100pF capacitors, a trimmer, and the 180kΩ resistors. The trimmer should be set so that the v.c.o. frequency at pin 4 is 56.3kHz with the tuning control in the centre position. With an R_1:R_2 ratio of 1:1 as shown, the frequency swing available should exceed that shown in table 3, and only the trimmer should need adjustment.

The second p.l.l. is used conventionally so that when its v.c.o. output frequency coincides with the incoming signal, the output of the phase comparator at pin 2 contains a d.c. component dependent on the relative phase. This output is fed back to pin 9 via a low-pass filter to hold the loop in lock. The p.l.l. is set up initially with the loop opened and pin 9 fed from a variable direct voltage. The required mid-frequency of 943.7kHz should be obtained with pin 9 at the middle of the range, between +4 and +6V. Because this frequency is near the device limit, it may be necessary to vary R_1 slightly. After this adjustment the frequency range in table 3 should be well inside the control range of about 0 to 10V on pin 9. All p.l.l. settings should be finally checked using the permanent power supply shown in Fig. 5.

Component summary for basic system

	No.
P.c.b. E01 (special design)	12
P.c.b. E02 (special design)	3
Veroboards (code 09-0091D)	4
Mains transformer 15-0-15V 20VA	1
Bridge rectifier (e.g. W01)	1
Regulators, +12, +5, −12V	3
AY-1-0212 (GIM) multiple divider	1
4011 quad NAND	1
4016 quad switch	9
4024 7-stage counter	36
4046 phase-lock loop	14
4520 2 × 4-stage counter	24
741 op-amp	25
Transistors (e.g. Mullard BC548C)	1250
Diodes (e.g. 1N4148)	280
Crystal 1MHz	1
Edge connector, 59-way plus key position	19
Edge connector, 24-way plus key position	12
Tantalum bead capacitors, 1μF/35V	400
Ceramic capacitors, 100pf 2%	41
Trimmers 5-65pF	14
Filter capacitors	156
Other capacitors	25
Resistors ½-watt	2100

The list includes 4 × 741 and 9 × 4016 for mixing and stop switching.

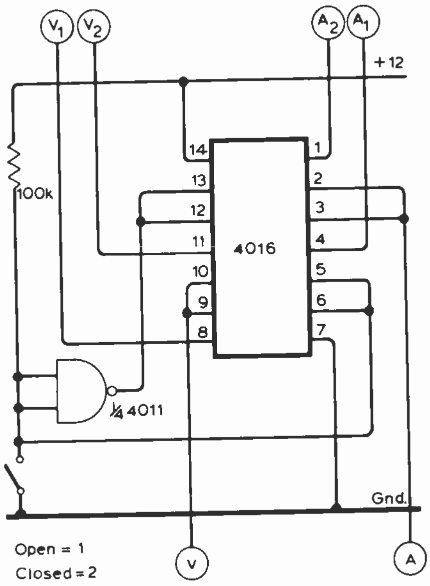


Fig. 7. *Change-over switch.*

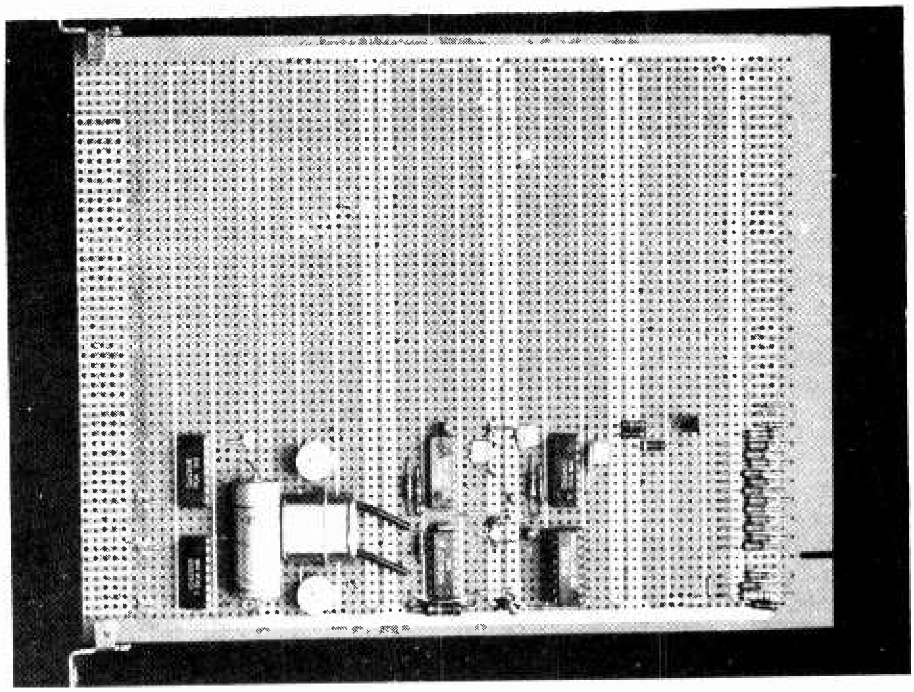


Fig. 8. *Prototype master oscillator including the standardising circuit. Space is available for additional functions.*

The locked output of the second p.l.l. also drives the divider. An optional standardising circuit is shown in Fig. 6. The first 4024 divides the v.c.o. frequency by 128, and the second 4024 divides the A reference by 8. A 4011 acts as a comparator so that when its inputs are in antiphase the output is high, and when in phase, the output is low for half of each cycle. Indicator calibration is

continued on page 91

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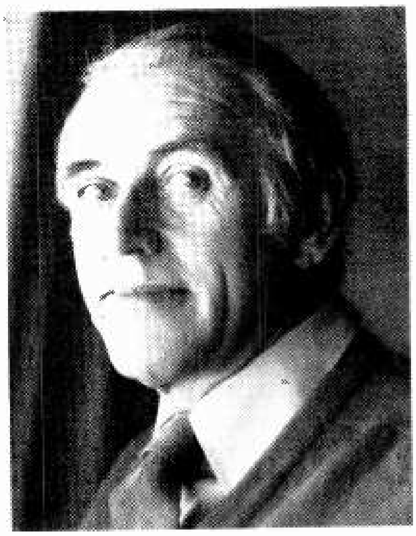
unimportant, and a different meter movement can be accommodated by changing the resistors.This indicator and tuning control may be remotely mounted.

If two sets of gate cards are used in an expanded system, it is possible to drive both sets from the circuit in Fig. 4 by changing the output resistors from 22kΩ to 10kΩ. This does not prevent the two sets from being independently frequency-modulated, but it does restrict them to the same tuning. To permit independent tuning the complete circuit of Fig. 4 should be duplicated beyond point X, which gives two sets of references from the crystal. The standardising circuit can be made switchable, and to avoid long a.c. leads a 4016 switch may be used as shown in Fig. 7.

The power-supply components are mounted on one side of the rack, which serves as a heat-sink for the regulators, see Fig. 1. The reference generator card uses a Veroboard as shown in the prototype assembly in Fig. 8. Edge-connection details are shown in Fig. 9. For the reference generator, positions 3 to 15, omitting 7, are reference outputs, position 16 is tuning and 17 is for the indicator.

For testing it is convenient to start with the crystal oscillator. The various frequency adjustments have already been referred to. If a frequency counter is not available an oscilloscope with a calibrated timebase can be used to measure the beat frequencies in table 2. If the crystal trimmer is set to mid range, the crystal should be very close to 1MHz. Supply currents for the prototype were +25 and −6mA.

David Ryder read Natural Sciences at Cambridge, but his career has been mainly in engineering. After a short spell in an instrumentation laboratory, he worked in the lift-manufacturing industry, and in the last few years has been concerned in the development of machine-tool controls. A lifelong interest in piano-playing, and a growing appreciation of the music of J. S. Bach led him recently to take up the organ. He says, "It is not surprising that an instrument with 600 years of development behind it can be an inexhaustible study, my organ lessons have been a first-class investment".

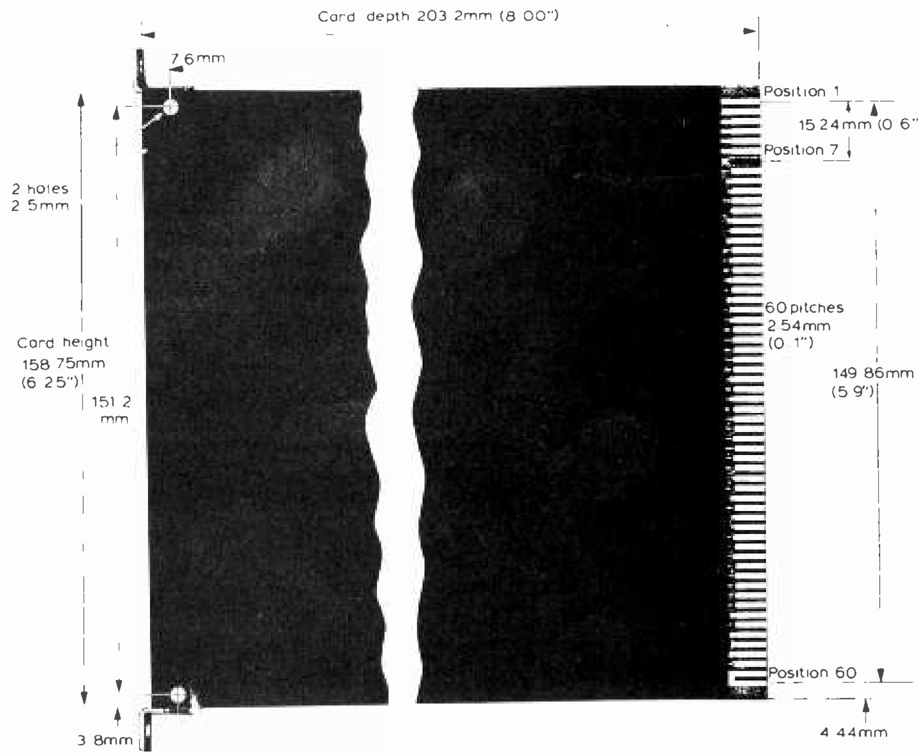


A 15 min cassette recording of the prototype is available for £2.00 c.w.o. A set of 15 special printed circuit boards (12 × E01, 3 × E02) is also available for £117.32 c.w.o. Both items are post free in the UK, and delivery is about 2 weeks and 4 weeks respectively.

Purchasers of these will also receive supplementary component and procurement details. Hiykon Ltd, Woodside Croft, Ladybridge Lane, Heaton, Bolton, BL1 5ED.

To be continued

Fig. 9. *Standard edge connections looking onto the copper side. The slot occupies position 7, and connections 59/60 are both ground. On cards requiring +12V, this is supplied via connections 1 and 2. The special cards E01 and E02 have 2.5mm fixing holes as shown.*



Corrections

Tunable audio equalizer. The photograph shown in Martin Thomas's design for a tunable audio equalizer in the September issue was of David Russell, author of Trends in microprocessors (who says for "single-chip microprocessor" read single chip microcomputer). "No disrespect intended" responds Dr Thomas "but I hope that the article with my photo doesn't turn out to be about a UFO detector, electronic personal vibrator or a remote-controlled plant waterer, to name but a few diabolical probabilities!"

Apologies to both authors, and to readers for other errors in that article. In Fig. 3 the bottom end of R_5 should be disconnected from earth and connected to IC_5 output. The right-hand side of the expression for bandpass centre frequency on page 59 should have been within a square-root sign. An oblique stroke should appear in the $s^2\omega_0^2$ term in the transfer function beneath to read s^2/ω_0^2. And in the state-variable filter box on page 62, *HPinput* should have appeared as *HP/input*.

Loudspeaker system design. In Fig. 13 of Siegfried Linkwitz' article (June), the bottom end of the 34.8kΩ resistor at the inverting input of the lower-left op-amp should connect to the other channel, and not to earth as shown. In Fig. 18 the square-root sign should not extend over the term including frequencies. Mr Linkwitz adds "the B110 is connected out of phase relative to the T27 and B139 because of a 180° phase difference between the channels in Fig 13." And that "741 op-amps should not be used in the buffer and tweeter stages if more than 2V peak is required from the tweeter channel to drive the power amplifier into clipping. Instead, faster and wider badwidth amplifiers are recommended to avoid potential s.i.d." Finally, on page 53 of the May issue, centre column, for 85dB read 95dB.