SECTION 5

Applications

TOOL CLASSIFICATION AND PERFORMANCE

Tools operated by compressed air can adopt a variety of different forms as in Table 1. They can be broadly classified according to the method of operation – percussive, rotary or combination (a combination tool is one in which percussion and rotation is provided pneumatically in the same tool, as in some rock drills and impact wrenches). A further broad classification is according to the place of use – the usual distinctions being industrial (or workshop) tools for factory operations, contractors tools for use on construction sites, and mining tools for quarry and underground use. Although the general principles of design are the same, the practical realisation of those principles can be very different according to the needs of the user.

Industrial tools form part of the total factory environment and as such they may be automatically operated and controlled. In a factory, tools which rely for their motive power on compressed air may nevertheless for convenience be controlled electrically.

In other situations, for example in mining and quarrying operations, the percussion action of a tool may be generated pneumatically whilst the rotary action may be hydraulic. The optimum configuration uses the ideal properties of each medium.

Performance information

Table 2 provides data for typical air consumption of tools. There is much variation between manufacturers. Efficiency is always improving, so it is wise to obtain up-to-date values direct from manufacturers. Air consumption figures are always available but other performance figures for tools are not so easily obtained.

Torque values for air motors, screwdrivers and nutrunners should be supplied and are easily checked by a conventional dynamometer, but the energy output of percussive tools is rarely provided, and for good reason. It is only in recent years that reliable techniques for the measurement of blow energy in percussive tools have become available, these are now embodied in BS 5344.

The technique described in that standard requires the use of strain gauges attached to the drill or chisel bit of the tool. When used with the appropriate analysis equipment, the energy content of each shock wave can be determined. Before this standard was

TABLE 1 – Tool classification

Portable rotary tools for removing material	
Drill	A rotary tool driving an output spindle generally through a gear box. The output spindle is normally fitted with a chuck or Morse taper or other socket, making the tool suitable for drilling, reaming, tube expanding and for boring metal, wood and other materials.
Straight drill	A drill with the rotary tool in line with the handle.
Piston grip drill	A drill where the handle of the tool is at an angle to the motor and the chuck axis.
Angle drill	A drill with the rotary cutting tool at an angle to the motor axis.
Grinder	A rotary tool driving an output spindle adapted to carry an abrasive device.
Straight grinder	A grinder where the handle, motor and spindle are in line.
Vertical grinder	A grinder where the handle or handles are at right angles to the motor and spindle axis which are in line or parallel.
Angle grinder	A grinder where the output shaft is usually driven through bevel gears so that the output spindle is at an angle (usually at a right angle) to the motor axis.
Straight die grinder	A small straight grinder for use with collets and mounted points.
Angle die grinder	A die grinder where the output shaft is driven through bevel gears so that the output spindle is at an angle (generally 90°) to the main axis of the tool.
Shear	A rotary pneumatic tool having a cutter reciprocating relative to a fixed cutter and used for cutting sheet metal by means of a shearing action.
Nibbler	A pneumatic tool for cutting sheet metal by means of material removal by reciprocating a punch through a fixed die.
Portable percussive tools	
Chipping/caulking hammer	A tool for chipping, caulking, trimming or fettling castings, welds, etc.
Scaler/scaling hammer	A tool for removing rust, scale, paint, *etc* through one or several reciprocating work pieces.
Needle scaler	A tool fitted with reciprocating metal needles for rust or scale removal.
Bush hammer/scabbler	A tool for surfacing stone *etc.*
Stone hammer	A tool for carving and working stone for sculpture purposes.
Sand rammer	A tool for ramming sand in foundry moulds by means of a butt attached to an extension of the piston.
Backfill rammer/tamper	A tool for consolidating earth *etc.*
Paving rammer	A tool for levelling paving-stones.
Tie tamper	A tool for tamping ballast beneath the sleepers of railway track using a special ancillary tamping tool.

TABLE 1 – Tool classification *(continued)*

Concrete breaker/pavement breaker/road breaker	A tool for breaking up concrete, rock, brickwork *etc.*
Sheet pile driver	A tool for driving sheet piles.
Pile driver	A tool for driving steel or wooden poles.
Sheet pile and pile extractor	A tool for extracting piles and sheet piles.
Spade	A tool fitted with a spade for digging clay, loam or peat.
Pick hammer/pick	A tool for light demolition or mine work.
Percussive tools with rotation	
Rock drill	A tool for drilling holes in rocks, concrete, *etc.*
Blower-type rock drill (blowing rock drill)	A rock drill fitted with a device for blowing out drilling chips with compressed air; usually the air passes through a hole down the centre of the drill steel.
Wet type rock drill (with water flushing head)	A rock drill fitted with a device for washing out drilling chips with pressurised water. *N.B.* Some rock drills may combine both air blowing and wet flushing.
Dry suction rock drill	A rock drill fitted with a device for the removal of drilling chips by suction.
Feed leg/air leg	A telescopic leg on which a rock drill can be mounted producing the thrust required for penetration and hole drilling.
Sinker or jackhammer	A hand-held rock drill used to drill vertical holes in rock. Its prime use is for sinking shafts and for quarry work.
Plug drill	A light hand-held drill for small holes in rock. Used in conjunction with a plug and feathers for splitting larger pieces of rock.
Stoping drill/stoper	A rock drill for drilling holes vertically upwards in a mine stope. Consists of a drill mounted on the end of a pneumatic cylinder.
Fixed pneumatic tools (rotary)	
Air motor	A pneumatic motor for driving.
Drilling unit	A pneumatic drilling tool with a feeding (and rectracting) device to be used as a component of a special machine tool.
Drilling unit with manual feed	A drilling tool with manual feed through a rack or any other means.
Drilling unit with automatic feed	A drilling tool with a feed controlled by a built-in powered feed device with adjustable stroke.
Tapping unit	A tapping tool with a built-in powered device with adjustable stroke.
Grinding unit	A straight or angle drive grinder designed for mounting on special grinding machine-tools or as a rapid grinding spindle on lathes.
Supported percussive tools	
Pile driver	A tool for driving steel or wood piles. Often this is an adaption of a road breaker.

TABLE 1 – Tool classification *(continued)*

Pile extractor	A tool for extracting piles.
Rock drill drifter	A percussive tool of heavy construction with rotating chuck for drilling holes in rock, used with a suitable support.
Carriage rock drill	A drifter, slide mounted on a carriage or cradle. The carriage can be mounted on a wagon drill, crawler, hydraulic boom, *etc*. The feed of the drifter along the carriage can be by chain, screw or cylinder.
Down-the-hole hammer	A hammer which is placed at the end of a drill rod and entirely enters the hole as it is being drilled. Rotation is effected by an independent motor turning the drill rod to which the hammer is attached.
Stone breaker	A heavy percussive machine mounted on a tractor for breaking stone, concrete, *etc*.
Pneumatic machines for assembly work	
Portable rotary machines	
Screwdriver	A rotary, reversible or non-reversible tool driving a spindle fitted with a screwdriver blade.
Straight screwdriver	A screwdriver where the axis of the bit is in line with the handle.
Pistol grip screwdriver	A screwdriver where the handle of the tool is at an angle to the motor and bit axis.
Stall-type screwdriver	A screwdriver without a clutch.
Clutch-type screwdriver	A screwdriver fitted with a clutch which may be adjustable.
Automatic clutch-type screwdriver	A screwdriver fitted with a clutch ensuring drive disengagement as a set torque is reached.
Automatic clutch-type screwdriver with air flow cut-off	A screwdriver fitted with an automatic clutch which actuates motor cut-off once a preset torque is reached.
Automatic clutch-type screwdriver with push start and air flow cut-off	A screwdriver fitted with an automatic clutch with axial push start by pressure on the bit, and automatic cut-off as a required torque is reached.
Angle screwdriver	A screwdriver with or without a clutch where the axis of the output spindle is at an angle to the motor axis.
Screwdriver with automatic feed of fasteners	A screwdriver with automatic feed of the screws *etc*.
Studrunner	A reversible nutrunner fitted with a special chuck for stud running.
Nutrunner	A rotary reversible or non-reversible machine driving a socket adapter.
Stall type nutrunner	A nutrunner where the only means for setting the tightening torque is by air pressure regulations.
Torque nutrunner	A nutrunner where the setting of the tightening torque is achieved by means of a clutch or any other means.

TABLE 1 – Tool classification *(continued)*

Angle drive nutrunner (wrench)	A rotary machine incorporating a socket adapter, the output axis of which is offset or at an angle to the rotor axis.
Two-speed nutrunner	A nutrunner incorporating a speed reduction gear or second motor, with an automatic tripping device reducing the speed once the torque has reached a certain value.
Ratchet wrench	An angle drive wrench progressively rotating a socket by means of a ratchet and pawl coupling.
Impact wrench	A rotary machine fitted with a multi-vane or oscillating motor driving a hammer which periodically strikes an anvil to which a socket is attached.
Straight impact wrench	An impact wrench with the motor-axis, handle and output spindle in line.
Angle drive impact wrench	An impact wrench with the output spindle at an angle to the motor axis.
Torque controlled impact wrench	An impact wrench in which a device automatically cuts off the motor when a preset torque is achieved.
Portable percussive tools	
Riveting hammer	A percussive machine for forming rivet heads.
One-shot riveter	A riveting hammer which delivers a single blow for every depression of the throttle actuator.
Yoke riveter	A combination of a riveting hammer and a holder-on, one on each side of a yoke.
Holder-on	A hammer or piston acting as a counterset on a rivet, the other end of which is being riveted.
Squeeze (compression) riveter	A linear piston machine without percussion which forms rivets by squeezing.
Nailer (stapler)	A tool for driving nails (staples) with one or more strokes. The nail (or staple) feed is often automatic.
Pneumatic machines for mechanical handling	
Hoist	A device for lifting and lowering loads.
Winch or capstan	A pulling or hoisting appliance, incorporating a cable drum.
Rotary vibrator	A device with a motor rotating an eccentric mass for vibrating containers, *etc.*
Percussive vibrator	A percussive tool designed to generate vibration.
Immersion vibrator (poker/vibrator)	A vibrating tool designed to be immersed in a fluid, usually concrete.
Miscellaneous pneumatic tools	
Sand or shot blasting machine	A system for sand or shot blasting where the carrier medium is compressed air.
Paint spraying gun	A gun by which the paint is atomized.
Air starter	A pneumatic motor or compressor for starting engines.

TABLE 2 – Air consumption of pneumatic tools and appliances

Description of tool or appliance	*Litre/s (6 bar)*
Rock drills	
Drifter drill (cradle mounted), 75 mm	70
Drifter drill (cradle mounted), 82 mm	82
Drifter drill (cradle mounted), 100 mm	100
Hand hammer drill (jack hammer), 13 kg	25
Hand hammer drill (jack hammer), 16 kg	30
Hand hammer drill (jack hammer), 21 kg	40
Hand hammer drill (jack hammer), 28 kg	50
Plug drill	15
Sinker drill, 75 mm	70
Sinker drill, 82 mm	80
Stoping drill, light	40
Stoping drill, heavy	70
Pneumatic tools (percussive)	
Concrete breaker, 35 kg	35
Concrete breaker, 23 kg	30
Concrete breaker, 14 kg	25
Pile driver	35
Chipping and caulking hammer, light	5 and 7
Chipping and caulking hammer, medium	9
Chipping and caulking hammer, heavy (suitable also for $^1/_2$" hot rivets)	12
Riveting hammer, 20 mm rivets	12
Riveting hammer, 25 mm rivets	13
Riveting hammer, 32 mm rivets	15
Riveting hammer, 35 mm rivets	17
Auger drill, for coal	40
Deck planer, for wood decks	30
Tube cutter, for tubes up to 65 mm	25
Tube cutter, for tubes up to 60 to 100 mm	30
Tube expander, for tubes up to 60 mm	25
Tube expander, for tubes up to 75 mm	30
Tube expander, for tubes up to 100 mm	35
Pneumatic appliances	
Wrenches (rotary torque), for nuts 6 mm	5
Wrenches (rotary torque), for nuts 10 mm	10
Wrenches (rotary torque), for nuts 12 to 18 mm	15
Wrenches (rotary torque), for nuts 20 to 25 mm	20
Impact wrench, for nuts up to 18 mm	15
Impact wrench, for nuts up to 30 mm	25
Spray gun, small at 4 bar pressure	1
Spray gun, medium at 4 bar pressure	4
Spray gun, large at 4 bar pressure	10
Air gun or duster	4
Sump pump, 6 to 20 l/s	20 to 60

TABLE 2 – Air consumption of pneumatic tools and appliances *(continued)*

Description of tool or appliance	*Litre/s (6 bar)*
Air motors, up to 0.75 kW	20 (per kW)
Air motors, 0.75 to 4.0 kW	18 (per kW)
Air motors, over 4.0 kW	16 (per kW)
Pick, light	12
Pick, medium	13
Pick, heavy	18
Spader, light	15
Spader, medium	20
Tie tamper	15
Rammer, foundry, bench type	7
Rammer, foundry, floor type, medium	10
Rammer, foundry, floor type, heavy	14
Rammer, back fill trench type	17
Spike driver	30
Scaling hammer, valveless, for surface work	3
Scaling hammer, for large boiler tubes	12
Paint scraper	4
Stone tool, for lettering and light carving	3
Stone tool, for medium dressing	5
Stone tool, for roughing and bushing	7
Weld flux chipper	8
Pneumatic tools (rotary)	
Drilling machine, for 6 mm holes in steel	10
Drilling machine, for 9 mm holes in steel	12
Drilling machine, for 18 mm holes in steel	15
Drilling machine, for 25 mm holes in steel	20
Drilling machine, for 30 mm holes in steel	25
Drilling machine, for 38 mm holes in steel	30
Drilling machine, for 50 mm holes in steel	40
Drilling machine, for 75 mm holes in steel	50
(For wood boring, take next size smaller. For reaming and tapping in steel, take next size larger).	
Corner drills, as above	
Grinders, with 18 mm wheels	5
Grinders, with 50 mm wheels	8
Grinders, with 100 mm wheels	20
Grinders, with 150 mm wheels	30
Grinders, with 200 mm wheels	40
Saw, 150 mm	15
Internal vibrator, o.d. 62 mm	30
Internal vibrator, o.d. 75 mm	40
Internal vibrator, o.d. 113 mm	50
Internal vibrator, o.d. 140 mm	60

Note: The air consumption of tools and appliances operated by compressed air is expressed in free air per minute – FAD. The above air consumptions should be taken as a guide and are subject to variations in different circumstances, as is the nature of the work, condition of the tools, intermittent use. The figures given are based upon operation at approximately sea-level. For higher altitudes a slightly higher allowance per tool is necessary.

developed, the performance of a percussive tool was assessed by such unreliable methods as measurement of the permanent deformation of a soft pellet when hammered by the tool bit or by the height of the pressure pulse when the tool output is absorbed by an hydraulic buffer. These methods are now only used for comparison between similar tools, and should not be quoted as an absolute measure of tool performance.

Even when the stress energy content of the shock wave is known, it will not necessarily be helpful to the user of the tool, who is concerned primarily with the amount of material that can be removed or drilled. Another way of defining the power output of a percussive tool is to quote, for example, the drilling speed in a specified kind of rock, or the amount of concrete that can be broken by a concrete breaker in a given time, or the amount of steel that a chipping hammer can remove. None of these is particularly easy to measure under controlled conditions. The prospective purchaser should be aware of information presented in such a way when trying to compare different tools. There is really no alternative to actually trying out a tool in the circumstances of one's own application.

As a general statement, a tool made by a reputable manufacturer will have a power output proportional to the its consumption, and that is probably the best guide that can be given. The weight of the tool is another useful indication of the power, but it should not be assumed that more actual work will be done by the heavier tool.

A further warning should be given when assessing raw performance data. At first sight it might be thought desirable to choose the tool with the highest output, paying no regard to the ease of use. All tools require the operator to apply a feed force and to sustain the vibration present at the handle. Usually a tool with the highest performance is the hardest to handle, but some tools are proportionally worse than others in this respect. Many tools are coming on the market which have been designed for ease of use; feed force, vibration levels and noise have been reduced, although sometimes at the expense of bulk and manoeuvrability.

Performance related to air pressure

Table 2 quotes air consumption for a variety of tools at 6 bar gauge pressure. Most manufacturers use this as a standard at which to measure performance, in spite of 6.3 bar being the recommended ISO standard; most compressed air systems should be capable of supplying this pressure as a minimum. The performance at other pressures is not necessarily proportional to the pressure. Theoretically the power output of percussive tools varies according to $(\text{pressure})^{1.5}$, but tools are designed to work ideally over a limited range of pressures, and they may not work anything like as well at a different pressure.

Some tools, particularly rock drills and down-the-hole machines for quarrying, work at much higher pressures (up to 20 bar). The reason for these high pressures is the need to maximise the drilling speed within the restricted space limitations of the tool. The overall efficiency of power conversion in high pressure tools may be lower than for standard pressure tools, but efficiency is less important than high performance in these applications.

INDUSTRIAL TOOLS

Rotary tools

Most rotary tools employ a vane type motor. This is the simplest and cheapest motor available and it can be made in a small diameter suitable for hand tools. Vane motors have a low inertia which means that they quickly reach maximum speed. Stationary machinery such as hoists and winches tend to employ piston and gear motors which are more robust and can withstand frequent stopping and starting. For high speed die grinders and increasingly for angle grinders, turbine motors are used.

Rotary tools can be divided into:

- grinders and sanders
- drills, tappers and reamers
- screwdrivers, nut runners
- impact wrenches
- impulse wrenches, impulse screwdrivers
- miscellaneous

Grinders and sanders

Figure 1 shows three common kinds of grinder. A die grinder uses a small diameter wheel for access to awkward corners and the bottom of dies. Each wheel has a maximum permissible rotary speed which must not be greater than the free speed of the grinder. Attention must be paid to ensuring that the designated speed on the blotter of the wheel cannot under any circumstances be exceeded. In the case of a die grinder, the free speed can be as high as 100 000 r/min, and special precision collets are needed to mount the grinding points. BS 4390 should be referred to for safety requirements; as well as information on safe speeds, it gives design parameters for the construction of safety guards.

The larger sizes of grinders (for wheels greater than about 50 mm diameter) are equipped with a centrifugal governor, which ensures that the free speed is limited to about 10 000 r/min. Smaller grinders have to rely on the limitation imposed by the maximum air

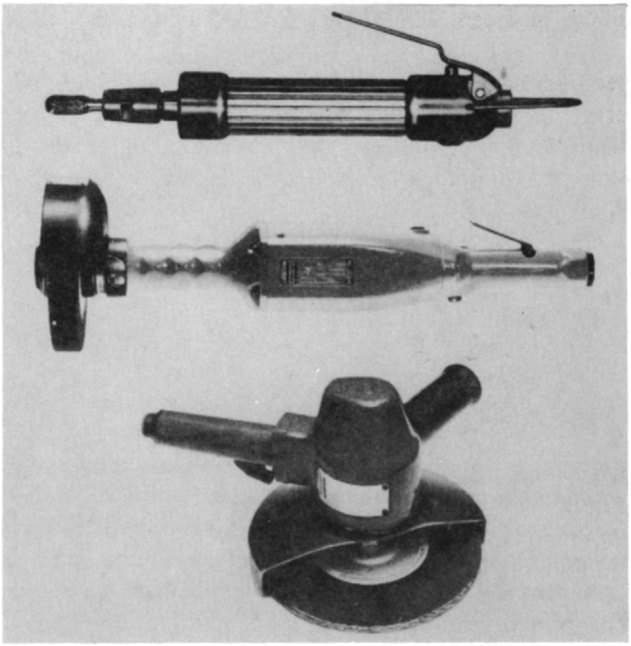


FIGURE 1 – Three types of pneumatic grinders.
A die grinder, straight grinder and vertical grinder. *(Atlas Copco)*

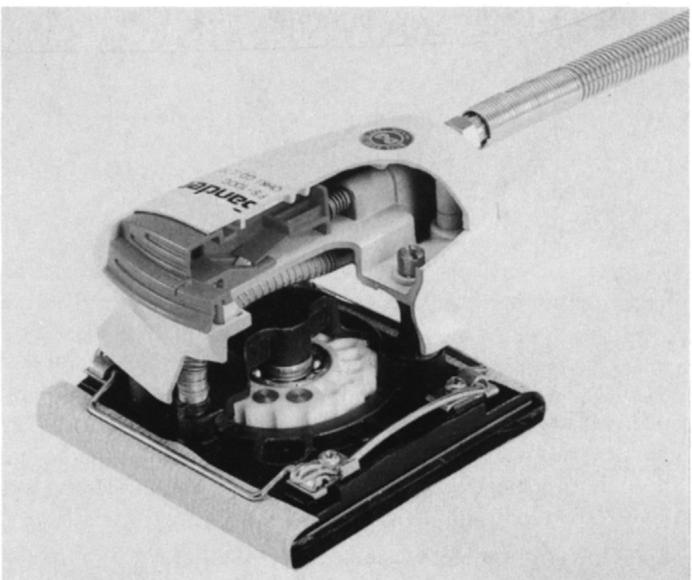


FIGURE 2 – Orbital sander cut away to show turbine motor.
20 000 rev/min. Consumption 0.2m^3/min. *(Nitto)*

flow through the inlet passages. Grinders are supplied with safety guards, which must always be used.

Different shaped wheels are available: cylindrical wheels, cup wheels, depressed centre wheels and cut-off wheels. A variety of special shaped points and tungsten carbide burrs are provided for die grinders.

Rotary sanders are essentially the same as vertical grinders but fitted with a sanding disc in place of a grinding wheel. Orbital sanders driven by a turbine are also available. One example using sanding paper and suitable for fine finishing is shown in Figure 2.

Theory of grinding

Grinding is a process that involves material removal using a succession of cutting edges. As the grains penetrate the material being ground they become worn, and the cutting force increases until they fracture and break out, revealing new and sharp grains. This gives a degree of self-sharpening which depends on the matching between the composition of the wheel and the material being ground. The choice of composition and grain size of the wheel is largely a matter of personal experience and choice. Usually a fine finish is not required of a hand grinder, in contrast to stationary grinders used in a machine shop, so a coarse grit for maximum stock removal is to be preferred.

All grinding wheels have a maximum speed which depends on their composition. BS 4390 sets the following limits on speed:

Type of wheel	*Diameter (mm)*	*Thickness (mm)*	*Max. surface speed (m/s)*
Reinforced resin-bonded straight wheels	50 – 200 50 – 200	6.5 max over 6.5	90 80
Reinforced resin-bonded depressed centre and cut-off wheels			80
Resin-bonded (resinoid) all types			48

The power curve of an ungoverned air motor, on which the design of grinding machines is based, peaks at about half the free speed (refer to the chapter on Air Motors), and this represents the condition at which maximum metal removal is possible. On a governed tool, the peak power point varies from 75 to 90% of the free speed. Most operators are able to judge the best speed fairly accurately with experience. The operator has to press down on the handles, and this force added to the dead weight should be sufficient to realise the ideal working speed.

Pneurop have organised extensive tests on hand-held grinders in assessing the vibration experienced by the operator of the tool ("Investigations on hand-held grinding machines", obtainable from BCAS). It appears that most of the vibration derives from unbalance in

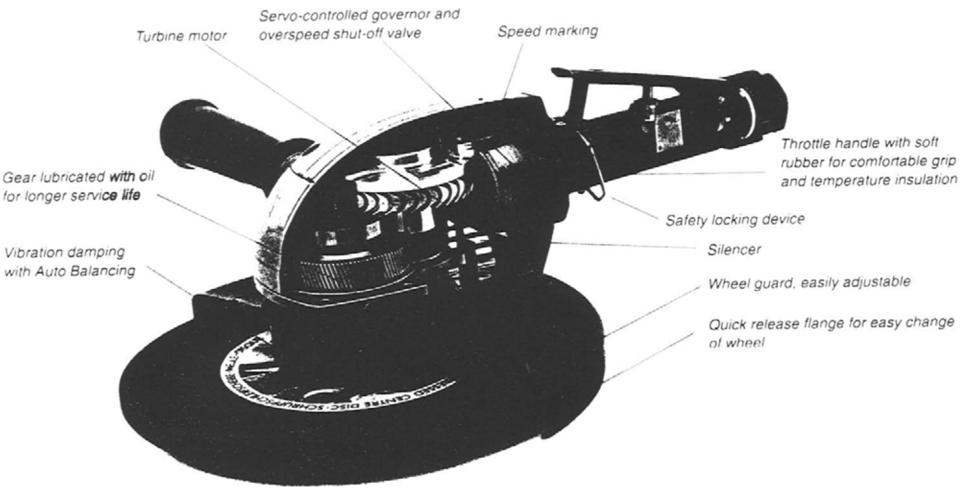


FIGURE 3 – Angle grinder cut away to show features. *(Atlas Copco)*

the wheel, rather than the cutting operation. This unbalance comes either from geometric changes, *eg* ovality, eccentricity of the centre hole or thickness variation. It may also be induced by uneven wear, or from uneven density in the composition of the wheel; it is possible for a wheel that is initially balanced to develop an unbalance and vice versa. It has been established, contrary to a common belief, that a vibrating tool is not more effective at removing material than a well balanced one. This reinforces the importance of regular dressing of the wheel. The exposure of grinding wheel operators to vibration should be monitored and their time at work restricted.

There are now becoming available hand grinders which incorporate devices which compensate for wheel unbalance. One example is the vertical (angle) grinder of Figure 3 which has a counterbalance mechanism employing bearing balls.

See the chapter on Noise and Vibration for further information.

Screwdrivers and nut runners

A selection of screwdrivers and nut runners is shown in Figure 4. For access to awkward places double angle wrenches are available. Wrenches are provided with square drive to accept standard sockets.

These tools transmit the torque either by direct drive or through a clutch. Direct drive relies on the operator to assess the applied torque, which can be as much as the stall torque of the motor or rather more if account is taken of the inertia of the motor. Clutches are of two broad types – slipping or torque release; the former type slips at the set value of the torque; the latter cuts off the supply of air to the motor. Magnetic clutches are also available. See also Figure 5. These tools have to be reversible, but usually the clutch does not operate when undoing.

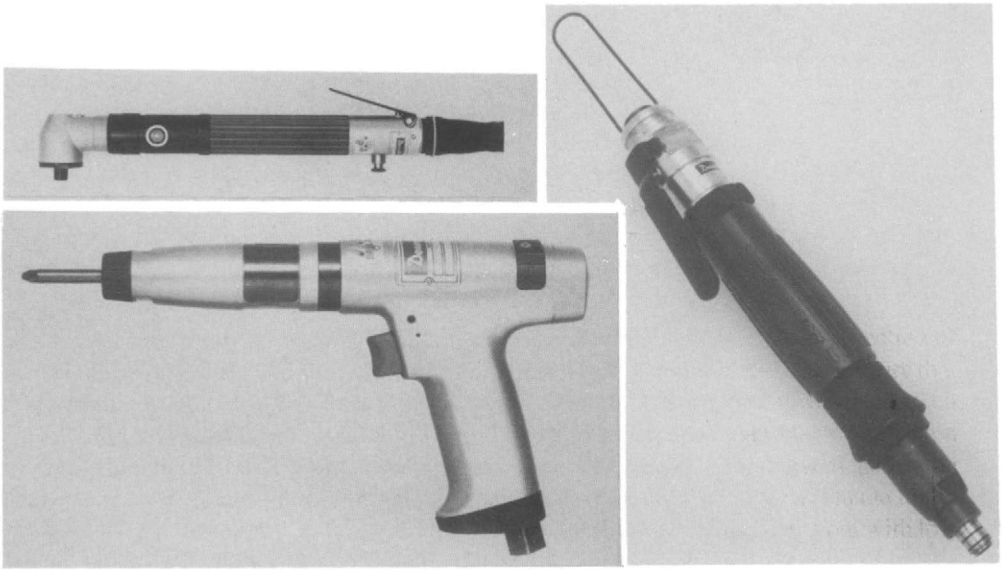
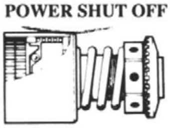


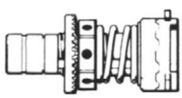
FIGURE 4 – Angle head nut runner (angle wrench), pistol grip screwdriver and straight screwdriver with ergonomic grip. *(Desoutter)*

TORQUE CONTROL POWER SHUT OFF



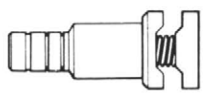
Torque is transmitted through two ramped clutch members which need only the smallest axial movement to simultaneously disengage the drive & shut off the motor. This clutch ensures excellent torque accuracy & minimal mean-shift on most applications

SPRING TENSION



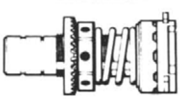
The clutch faces ride up and slip over each other when the preset torque has been achieved. The spring tension clutch is a good general purpose clutch.

POSITIVE



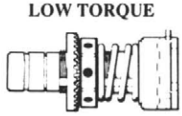
Torque transmitted by the positive clutch is proportional to axial thrust exerted on the screwdriver. This feature makes it ideal for woodworking & self tapping applications where the torque needs to be "driven up" to overcome variable resistances – *ie* knots.

FRICTION



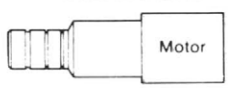
One clutch face is flat so only friction between faces has to be overcome. Excellent clutch for very light duty applications such as self tapping in plastics.

LOW TORQUE



Similar in operation to the spring tension or the one shot clutch, but with the clutch face ramp angle reduced.

DIRECT DRIVE



The direct drive between screwdriver bit and motor ensures maximum available torque from the motor is transmitted. Variable torque is achieved by varying tool inlet pressure – stall point.

FIGURE 5 – Types of clutch for screwdriver and nut runners. *(Desoutter)*

Drills, tappers and reamers

These are similar in construction to screw drivers. The larger sizes carry a standard chuck; the smaller sizes employ a collet to grip the drill bit. Tappers can incorporate a reversing mechanism which automatically withdraws the tap at double speed when the cutting operation finishes.

Precision feed drilling

For precision drilling in the aerospace industry and wherever high quality performance is required, a variety of controlled feed mechanisms are available. The following are typical examples:

1. The controlled feed drill has an automatic feed/drill/retract cycle, all operated pneumatically on a hand held tool. The complete cycle is initiated by depressing the trigger. Hydraulic damping controls the feed rate to minimise burring on break-through, and the trigger can be locked to allow simultaneous use of more than one unit.
2. The automatic feed drill is similar, but in this case the cycle is initiated by touch of a button and allows for remote start/stop signals, ideal for robotic or special purpose machine applications.
3. Variable feed drills combine power feed with manual feed. The manual feed allows for rapid advance and retraction, and for such applications as swarf clearance when deep hole drilling.
4. Rack feed drills rely on manual feed and retraction, although automatic stop and start of the motor is possible at any point in the stroke.

Combination of air and electric motors for special applications are also available – it is possible to have air feed combined with an electric drill, and also both feed and drilling performed electrically.

Impact wrenches

These are rotary vane motors with an additional rotary impact mechanism to impart a blow as the resistance increases (Figure 6). Impact wrenches are available to apply a torque of up to 100 000 Nm or more with an output drive of $3^1/_2$ in. The motor first runs freely until the nut offers resistance to the torque, whereupon the impact mechanism comes into play to assist further tightening. It is possible to exert high values of torque with small reaction

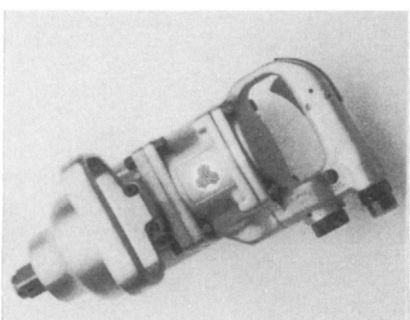


FIGURE 6 – Impact wrench. 1" socket, 2500 Nm torque. *(CompAir Power Tools)*

on the operator. Some types have an adjustable torque setting, ensuring that the tension in the bolt is not exceeded. Although the torque setting is unaffected by changes in air pressure, unless the available air pressure is 6 bar or greater the maximum setting of the torque may not be reached.

Various types of torque control are available, according to the manufacturer. Some have a device which cuts off the air supply when the torque setting is reached; some have a built-in timer which shuts off the air after a certain time; some have an adjustable restriction which limits the air supply. The first type is more accurate, but they all need to be calibrated on the joint to be tightened, which makes them more suitable for production runs than for the occasional tightening operation. Devices which work by cutting off the supply pressure rely on an ability to sense the amount of rebound off the tightened nut, followed by triggering a cut-off valve. With this method, the response depends on the stiffness of the joint; some tools work better with a stiff joint, some are better for a flexible joint.

For accurate torque settings, torque bars can be used. These are graduated extension bars, inserted between the wrench and socket. two kinds are available: adjustable and non-adjustable. They have a calibrated flexibility which is able to trigger a shut-off device when the torque is reached

Impulse tools

These represent a new development, which for many purposes are replacing impact wrenches, particularly for smaller sizes of bolt (for a torque range up to about 280 Nm and a driver size up to 3/4 in); see Figure 7. These have a conventional vane motor but instead

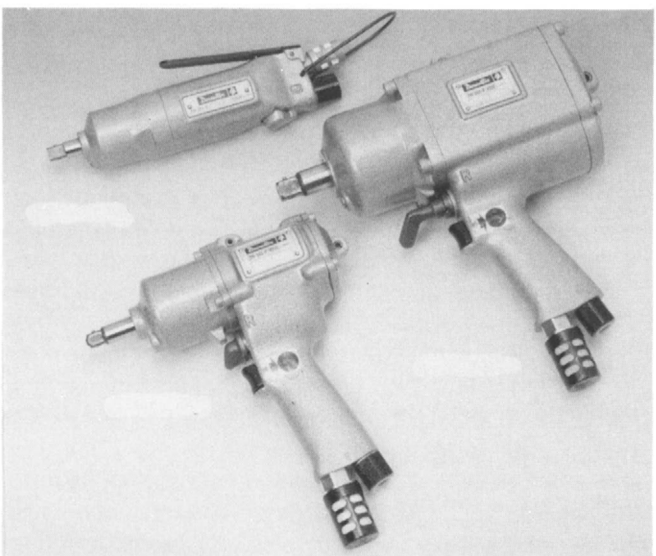


FIGURE 7 – Impulse wrenches: Straight case, torque 19Nm.
Pistol grip torque, 17Nm and 245 Nm. Note the torque setting control. *(Desoutter)*

of metallic impact, an impulse is applied to the output shaft of the tool through a rotating, cam operated, hydraulic piston unit. This results in high speed rundown, much quieter operation, repeatable torque settings and low vibratory reaction on the operator. The absence of metallic impact in the tool means that the service life is likely to be longer than for an impact wrench; a factor of 10 x has been quoted, but this will depend on the particular design.

As the impulse unit rotates and the cams engage every 360°, a pulse of energy is transmitted to the output shaft, increasing the fastener torque each time the cams engage. The torque is set by a control knob on the body of the tool.

These tools also incorporate a shut off mechanism which acts to divert the energy of the tool and restrict the supply of air when the resistance of the bolt reaches the torque setting.

Considerations of joint tightness

Although the use of a calibrated torque wrench to control the degree of tightening of a bolted joint is an advance over relying on the feel of the operator, it is not as reliable as a method which directly measures the tension in the bolt. Friction is the dominating influence in trying to correlate the torque with the bolt tension. The coefficient of friction is not easily determined: it varies with the amount of lubricant present, the condition of the mating surfaces and variation in the geometry of the joint. A high degree of accuracy in the applied torque is unlikely to decrease the inherent scatter in the bolt tension values. Two methods have been developed to overcome this problem.

The first method is known as Angle-controlled Tightening. It is a method of indirect elongation measurement avoiding the practical difficulties inherent in trying to assess the total bolt stretch from head to point. Angle-controlled tightening measures the movement of the nut relative to the clamped component after the mating surfaces are fully seated. The stretch of the bolt and the tension in it can be calculated from the angular movement of the nut and the pitch of the thread.

A plot of torque versus deflection would show a distinct knee in the curve, at the point where the clamping action changed from bringing the surfaces together to stretching the bolt, and it is from this point that the angular movement is measured.

Practical experience in the use of this method indicates that high precision is obtained only if the bolt is tightened beyond its yield point, which is satisfactory in many applications but in others, as for example in joints where the clamping length is short or where the material is brittle, the bolt may be overloaded. The method is unsuitable when bolts experience a working tensile load which adds to the pre-load. Bolts which have been stressed into the plastic region cannot be reused.

A second, more accurate method, known as Gradient-controlled Tightening has been developed. This method, instead of measuring the angle alone, measures both torque and angle and calculates the slope of the torque/angle curve. As soon as this slope reaches the yield point, the air supply is cut off. This technique is only suitable for use on a production line in conjunction with the appropriate electronic analysis equipment; however for less sophisticated applications a portable calibrated torque wrench is available which measures the gradient and can be used to calibrate a power driven wrench and for quality control.

Percussive tools

Percussive industrial tools include:

- chipping hammers
- scaling hammers
- rivetters
- sand rammers

Chipping hammers

Chipping hammers are percussive tools used for a wide range of industrial purposes:

- removal of welding slag and rust
- dressing castings
- chamfering steel plate for weld preparation
- bolt and rivet shearing

Table 1 enables a choice to be made of the correct size of hammer.

TABLE 1

Tool weight kg	*Frequency blows/min*	*Recommended duty*
1.5	3500 – 5000	Very light chipping, rust scaling, panel cutting.
2.5	2000 – 3500	Light chipping, weld dressing, bolt and rivet shearing, driving shackle pins, caulking.
4.5	1500 – 2000	Aluminium and light cast iron dressing.
6.0	1500	Heavy cast iron and light steel dressing.
6.5	1500	Heavy steel dressing.

Chipping hammers of a traditional design produce high levels of vibration, and operators who spend most of their working time using one for foundry fettling or some other continuous operation should be monitored for signs of vibration injury (see chapter on Vibration Exposure).

Figure 8 shows an example of a modern vibration reduced chipping hammer. The design of this tool has succeeded in reducing the vibration level when compared with a conventional tool (a claimed reduction from a weighted vibration of 10.5 m/s^2 down to 2.1 m/s^2).

Chipping hammer chisels are made in a wide choice of shapes to suit different purposes, Figure 9. Shanks can be hexagonal or round, according to manufacturer's choice; chisels are not necessarily interchangeable between manufacturers, although BS 673 specifies standard dimensions which most manufacturers follow.

Some of the hammers are provided with a boss on the handles for attachment of an

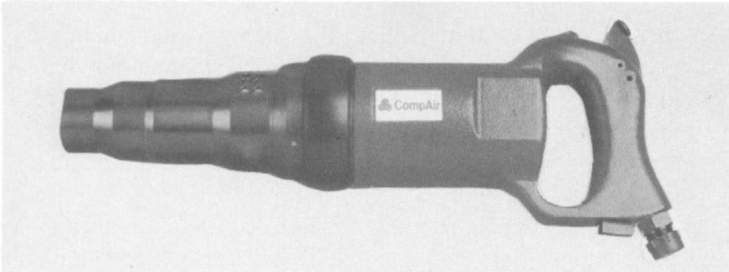


FIGURE 8 – Vibration reduced chipping hammer. *(CompAir Power Tools)*

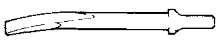
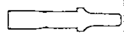
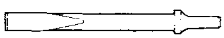
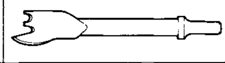
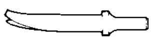
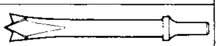
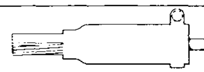
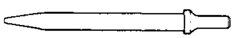
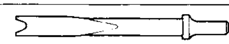
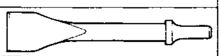
Description	Shape	Description	Shape
Rivet Cutter		102mm Flat Chisel	
179mm Flat Chisel		3-way Silencer Cutter	
Edging Tool		25mm Forked Chisel	
Double Edge		Needle Scaler	
Punch			
Spot Weld Splitter			
Paint Scraper			

FIGURE 9 – Tool attachments for chipping hammers. *(Desoutter)*

FIGURE 10 – Vibration reduced needle scaler. *(CompAir Power Tools)*

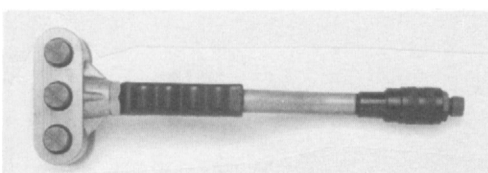


FIGURE 11 – Triple head scaler. *(CompAir Power Tools)*

exhaust hose which can be led away to a silencer. It should be borne in mind, when using a silencer, that it may make the tool rather more awkward to handle and may not significantly reduce the noise level, particularly if most of the noise comes from the actual process (drumming of the panel or ringing of the casting).

Scalers

These are similar to light chipping hammers, Figure 10. They are specially designed to remove scale and rust, and for surface preparation. They are available either with a conventional chisel bit or with a bunch of hard spring steel or beryllium copper needles suitable for negotiating awkward shapes.

Figure 11 illustrates another type of tool designed primarily for surface dressing of stone and concrete.

CONTRACTORS TOOLS

The designation "Contractors Tools" refers to compressed air equipment used on construction and building sites. There is a degree of common usage between the three broad site classifications – industrial, contractors and mining. Thus chipping hammers may be used for metal dressing in a factory and for concrete dressing on a construction site. The needs of the miner and the construction site worker are also similar; a rock drill can be used for drilling rock on a road construction contract and for quarrying and mining. So the distinctions made here are somewhat arbitrary.

Road breakers

A common contractor's tool is the road breaker, paving breaker or concrete breaker. This is sometimes referred to as a road drill, but this is an incorrect usage; the term "drill" is restricted to those tools which either incorporate rotation as part of their mechanism or are separately and externally rotated. A road breaker has no rotation; it is a tool specifically designed to produce a heavy blow to break up road surfaces, and to perform similar allied functions. With the addition of various tool bits and chisels, it can also act as a clay spader, tie tamper, post-hole driver, back-fill rammer and pile driver. See Figure 1.

Modern road breakers are designed with a degree of exhaust muffling to reduce the possibility of noise damage to the operator. Some tools are available in both standard and muffled form, although it is unlikely that the standard form would be able to meet the EC limits for maximum noise level. The standard form may only be sold in those countries outside the European Union where noise regulations do not apply. Some modern tools are designed in such a way that they may only be used in the muffled form – the muffler forms an integral part of the construction which, if removed, would render the tool unusable. A number of manufacturers make tools of this kind. This has the advantage from environmental considerations that the tool may only be operated in the muffled condition.

Most mufflers make use of rigid polyurethane, a material which has demonstrated its ability to withstand the rough usage of a construction site. It can be moulded without expensive equipment, so it can be economically made up in small batches. It is available in a variety of colours.

Figure 2 shows a modern road breaker. It has many features common to other percussive

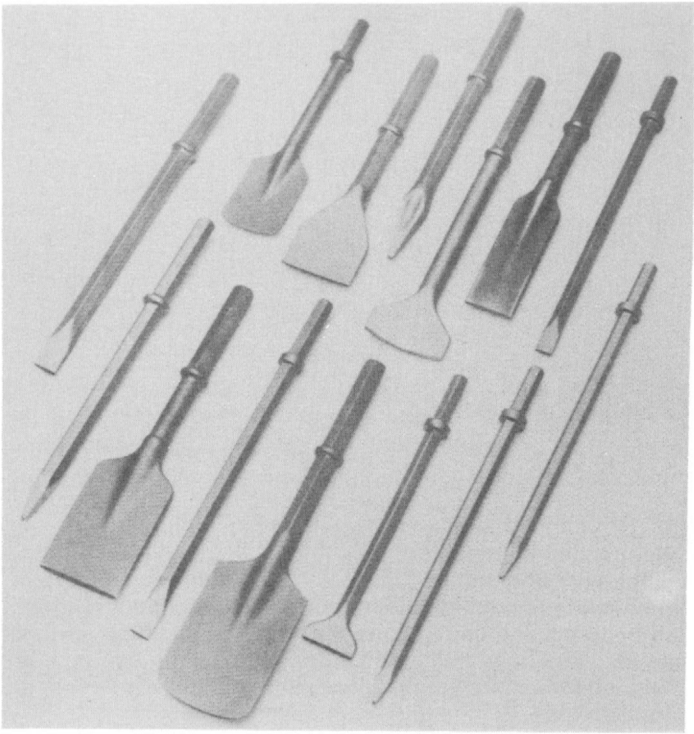


FIGURE 1 – A selection of accessories for use with road breakers. *(Padley and Venables)*
Clockwise from the left: narrow chisel, digger steel ($4^1/_4$ in), tarmac cutter, 'Easibust' steel, axe blade, digger steel, narrow chisel ($4^1/_4$ in), two moil points ($4^1/_4$ in), wide chisel, clay spade, narrow chisel, digger steel and moil point.

Accessories have shank sizes to match standard tool chucks. The available shank sizes are:
32 mm ($1^1/_4$ in) hex x 152 mm (6 in) long
28 mm ($1^1/_8$ in) hex x 152 mm (6 in) long
25 mm (1 in) hex x 108 mm ($4^1/_4$ in) long
22 mm ($^7/_8$ in) hex x 82 mm ($3^1/_4$ in) long

tools such as picks and spaders which incorporate a distribution valve. The method of operation is as follows:

Air is admitted through the main swivel connection. When the trigger is depressed, the ball valve opens admitting air to the distribution valve situated at the top of the piston. The valve in this example is a simple plate valve, although more complex shapes are also found. It is held on its top or bottom seat by differential pressures on the upper and lower surface: when the valve is on its bottom seat, air is directed to the under surface of the piston; when the valve is on its top seat, air passes to the top of the piston. When air is first admitted to the tool, both piston and valve are at their down position, so air passes into the bottom chamber of the cylinder forcing the piston up. Towards the end of its upwards travel, the piston compresses the air in the upper cylinder, which causes the valve to move on to the

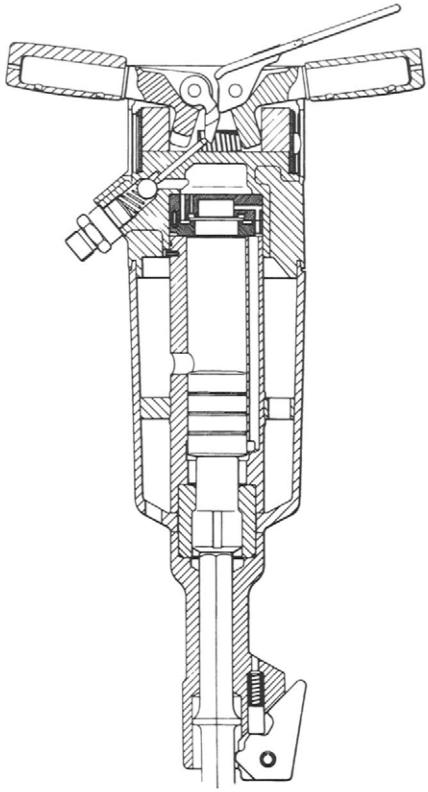
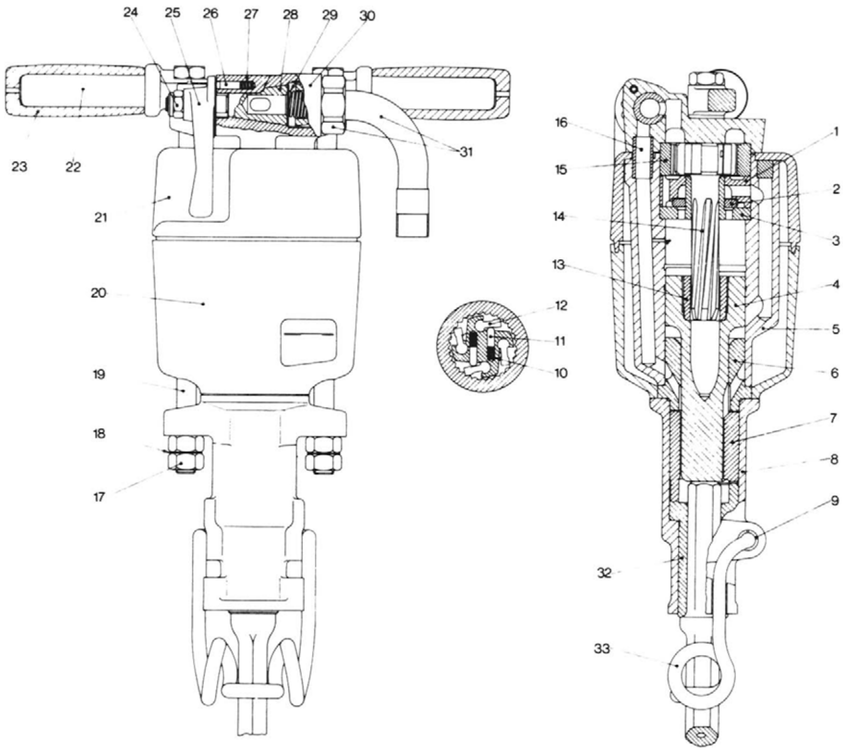


FIGURE 2 – A modern road breaker tool, cut away to show the construction. The components are held together by long side belts (not shown). Incorporated in the handle is an oil reservoir. *(CompAir Holman)*

opposite seat. At the same time the air in the bottom chamber exhausts to atmosphere via the passages in the muffler. The air then acts on the top of the piston forcing it down. When the piston impacts the anvil block, its energy passes into the chisel and then into the concrete to be broken. The air exhausts from the upper cylinder and the fall in pressure allows the valve to move once more onto its bottom seat. The cycle then repeats at a frequency, of the order of 1000 to 1500 rev/min, depending on the design and the air pressure.

The shank of the chisel is of hexagonal cross-section; the latch-type retainer keeps the chisel held in the front head by the collar on the chisel shank; round shanks are also found in picks where it is not required to turn the tool. A variety of different retainers are made: a latch type is illustrated and is the most common, but screw and spring types are also supplied.

Most tools incorporate an oil reservoir which dispenses a small amount of oil into the working parts of the tool each time the trigger is pressed. It is important to keep this reservoir topped up at least once during each shift, but this form of lubrication is not as



1.Valve chest
2.Valve
3.Valve chest front end
4.Piston
5.Cylinder
6.Clinder washer
7.Chuck driver
8.Front cover
9.Bushing
10.Spring
11.Plunger
12.Pawl
13.Rifle nut
14.Rifle bar
15.Ratchet ring
16.Connector
17.Nut
18.Washer
19.Side rod
20.Muffler
21.Muffler (rear)
22.Bar handle
23.Grip
24.Nut
25.Tumbler handle
26.Plunger
27.Spring
28.Tumbler
29.Spring
30.Backhead
31.Air swivel
32.Chuck
33.Retainer

FIGURE 3 – Hand-held rock drill. *(CompAir Holman)*

satisfactory as a separate lubricator inserted in the air line. The use of a specially formulated oil is recommended for this tool.

This tool also incorporates a vibration suppression device, which can be seen on the handles. The handles can pivot on a pair of pins and the anti-vibration element consists of a lateral spring and a rubber cushion. There is an increasing demand for some form of cushioning to meet health and safety requirements.

A range of contractors' percussive tools is shown in Figure 4.

Rock drills

Figure 3 is a cross-section of a typical modern hand-held rock drill, also illustrated in Figure 4. Superficially it has many similarities to the road breaker discussed above, but

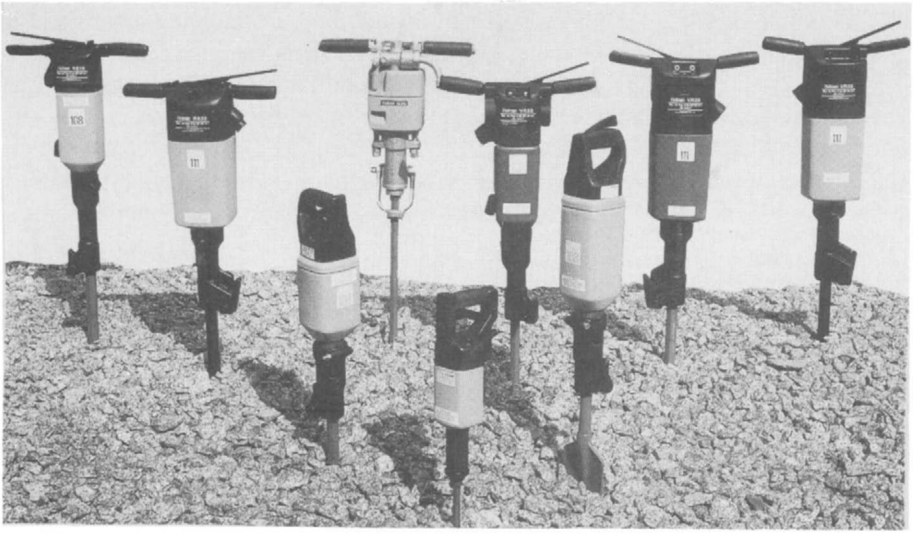


FIGURE 4 – A range of contractors' percussion tools. Left to right: 2 road breakers, a medium duty pick, a light weight rock drill with rotation, a light pick, a light road breaker, a road breaker with a 'D' handle, two road breakers. Note the numbers 108, 111 on the bodies, which are the sound power levels to satisfy EC regulations. *(CompAir Holman)*

there are some major differences. It has the same type of disc valve and the cycle of operations is similar except that, in addition to the reciprocation of the piston, the drill bit is rotated by an internal ratchet mechanism. The piston has an internally rifled bush which matches a similarly rifled bar held in the backhead of the drill; a ratchet mechanism ensures that the piston rotates only on the upward (or return) stroke. On the power (*ie* the down) stroke there is no resistance to the motion of the piston, so that the full pressure is available to produce impact energy. On the return stroke, the piston rotates along the rifling and transfers that rotation to the drill steel by means of straight splines on the trunk of the piston which mesh with similar splines on the chuck.

A rock drill of this kind incorporates a means for flushing out the drilled hole, which can be done either by air or water. Air flushing is either continuous, when air passes directly from the exhaust port or is under operator control by selection of the blowing position on the tumbler handle. In the latter alternative the full flow of the air passes down through the hole in the drill steel to give full pressure clearance. Water flushing, which is necessary underground where the dust has to be suppressed, is achieved by passing water from a separate connection on the backhead down a tube passing through the piston into the drill steel. The water pressure has to be kept at a minimum of about 1 bar.

This particular drill is capable of drilling a 45 mm diameter hole at a penetration speed of 180 mm/min in granite; in limestone and softer rocks , the drilling speed can be up to twice as much.

A rock drill has to stand much harder usage than a breaker. The blow frequency is higher and the level of energy is higher. The extra complication of the rotation mechanism underlines the need for good lubrication at all times, so a separate line oiler should be included in the air line feeding the drill, even though some manufacturers offer a drill with an oil reservoir in the handle for occasional use. The consumption of spare parts is high, particularly of such items as the chuck, the rotation ratchet and the rifle nut. Typically during the life of a drill, it will consume two to three times its first cost in spare parts.

One distinction between a drill and a breaker is the magnitude of the energy in each blow and the shape of the cylinder to produce that energy. A breaker has a long stroke and smaller bore, typically about 45 mm bore with 150 mm stroke, producing a heavy-hitting low-frequency blow. The hand-held rock drill described above has a 64 mm bore and a 48 mm stroke. The energy content of the individual blow is not so important as the total energy per minute, so the drill maximises that energy by increasing the frequency of operation.

Rock drills of this general type incorporating rifle-bar rotation can be as small as a miniature drill weighing 2 to 3 kg, consuming 12 l/s of air, up to the large rig-mounted drills weighing 150 kg and consuming 240 l/s. Even larger drills, with independent rotation (the rotation is achieved with a separate motor directly connected to the drill chuck) are available, weighing 300 kg, consuming 300 l/s. Drills heavier than 30 kg are not suitable for hand use.

Performance estimation of percussive tools

Estimating the performance of percussive tools is not a particularly easy exercise, when compared with their hydraulic or pneumatic counterparts. The difficulty stems partly from an uncertainty about the amount of expansion of the air at the point of use. Modern methods of analysis rely on computer simulation, for which specialist programs are available. A description of these methods is outside the scope of this volume and the interested reader is referred to one of the companies specialising in simulation techniques.

The "broad brush" method of analysis adopted here makes it possible to compare the performance of one tool with another, and enables the influence of the main tool parameters, such as bore, stroke and air pressure to be studied.

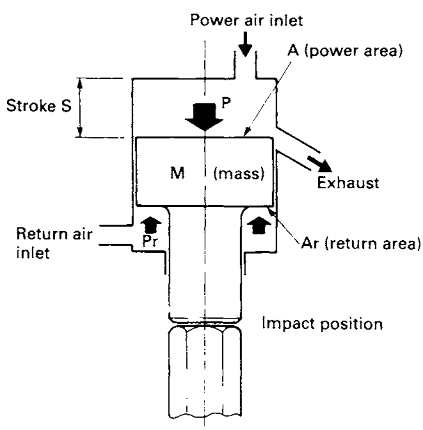


FIGURE 5 – Forces acting on percussive tool.

Figure 5 shows the forces acting on the piston of a percussive tool. The following quantities are derived from a consideration of the acceleration of the piston.

Work done on the power (impact) stroke = PAS

$$\text{Time for power stroke} = \left(\frac{2MS}{PA}\right)^{1/2}$$

$$\text{Terminal velocity} = \left(\frac{2PAS}{M}\right)^{1/2}$$

$$\text{Time for power and return stroke} = (1 + k)\left(\frac{2MS}{PA}\right)^{1/2}$$

where k is the ratio of the time spent on the return stroke to the time spent on the power stroke.

$$\text{Blow rate} = \frac{1}{1 + k}\left(\frac{PA}{2MS}\right)^{1/2}$$

$$\text{Total work output} = \text{Blow rate x work/blow} = \frac{PAS}{1 + k}\left(\frac{PA}{2MS}\right)^{1/2}$$

$$= \frac{(PA)^{3/2}}{1 + k}\left(\frac{S}{M}\right)^{1/2}$$

These equation are applicable when all units are consistent. In terms of the standard engineering units which have been used throughout, *ie* stroke in metre, area in $(\text{metre})^2$, pressure in bar and mass in kg they become:

Work done on power stroke = 10^5 PAS joule

$$\text{Time for power stroke} = 0.00447\left(\frac{MS}{PA}\right)^{1/2} \text{ s}$$

$$\text{Terminal velocity} = 447.0 \left(\frac{PAS}{M}\right)^{1/2} \text{ m/s}$$

$$\text{Time for power and return stroke} = 0.00447\,(1 + k)\left(\frac{MS}{PA}\right)^{1/2} \text{ s}$$

$$\text{Blow rate} = \frac{224}{1 + k}\left(\frac{PA}{MS}\right)^{1/2} \text{ per s}$$

$$\text{Total work output} = 22.4 \text{ x } 10^3 \text{ x } \frac{(PA)^{3/2}}{1 + k}\left(\frac{S}{M}\right)^{1/2} \text{ kW}$$

These equations give only an indication of the behaviour of a tool and as such are useful for estimating what is likely to be the result of changing the pressure or the dimensions of an existing tool. They are less useful when attempting to predict the performance of a tool off the drawing board. For such purposes, a more complex simulation, involving a computer analysis is required.

When considering the above expressions note that the pressure P is the mean effective pressure on the power stroke, which will generally be lower than the applied pressure at the inlet. Furthermore the mean pressure on the return stroke will be lower than that on the power stroke. The factor by which the inlet pressure is to be multiplied to get the effective pressure depends on the detail design of the tool, particularly that of the distributor valve. P on the power stroke will be about 0.6 times the inlet pressure and P on the return stroke will be about 0.4 times the inlet pressure. The return pressure and the area below the piston on which it acts will govern the value of k. Typically k will be 2.0 to 2.5.

The air consumption of a tool of this kind is theoretically equal to the total swept volume of the power and return stroke per second of the compressed air. In terms of the usual FAD (free air delivered), the pressure ratio must be taken into account.

$$\text{Air consumption} = \frac{224 \times 10^3}{1+k}\left(\frac{PA}{MS}\right)^{1/2} \text{PAS l/s}$$

This expression should be used with reservation. It takes no account of leakage and other wastage, which is inevitable because there are no seals on the piston. In practice the actual air consumption may be as much as 50% in excess of the calculated value.

Another expression may sometimes be useful. This concerns the external reaction force on the handle or on the support structure of a rig-mounted drill. It is a measure of the force that must be applied by the operator to use the power generated by the tool.

$$\text{Reaction force} = 10^5 \frac{PA}{1+k} \text{ N}$$

If the tool is held vertically, as for example the case of a road breaker, the operator applies the difference between this and the dead weight of the tool. Over a sustained period an operator cannot apply more than 100 N, and for short periods more than his body weight. It is this reaction force more than any other factor which limits the usable power of a hand held tool. If a tool were designed with a greater potential power, the operator would find it impossible to handle.

The reaction force calculated here is the mean static force. There is in addition a vibratory element, which varies with the tool design. Apart from vibration induced white fingers, a disease of tool operators, the presence of vibration at the tool handle represents a fatigue-inducing factor which may be more limiting than the static force.

Rotation systems

Another aspect of percussive tool behaviour, capable of theoretical estimation, is the torque produced by a rifle-bar rotation mechanism.

The function of this method of rotation should be understood first. The modern rock drill derives its action from the traditional method of hand drilling with hammer and chisel. The old time miners used to drill in teams: two men would wield hammers, and a third would hold the chisel and rotate it. The rock was broken by chisel action rather than by rotary cutting, and so it is in a modern rock drill; only in relatively soft rock such as coal and shale is it possible to drill by rotary action. It is easier to rotate a drill by hand in an anti-clockwise direction, so that is the direction that a drill turns. Smaller drills that can be used for both rotary and impact drilling are also fitted with clockwise rotation; and the heavier rock drills, using coupled rods that have to be screwed together, include a facility for reversing the direction of rotation to allow for uncoupling of the rods. Some stoper drills, which serve the dual purpose of drilling and acting as torque wrench for roof bolting, are also equipped with a clockwise rotation mechanism.

A rock drill must be forced against the rock by a feed force having the magnitude given in the equation above. The applied force should be just sufficient to keep the bit in contact with the rock, but no more. As the bit rebounds after the rock is broken, there is no resistance to rotation, and so a comparatively small torque is needed just to index the bit to the next cutting position. Air or water removes the chippings so that the chisel action is not cushioned by drilling detritus.

It is for this reason that the rotation occurs on the return stroke of the piston. The angle of the splines on the rifling is just sufficient to index the bit by about 20 to 30 degrees per blow, so that while the blow frequency may be of the order of 2000 per minute, the rotational speed will be about 100 per minute. It is usual in English usage to refer to a drill having a rotation (for example) of 1 in 30, as meaning that the bit rotates by one complete turn for every 30 inches of travel of the piston – a lead of 30 inches. Common values of lead are 30, 35, and 40. In SI units, the lead can be expressed in mm.

The shallowness of the angle of the rifle-bar, used to achieve such a slow rotation, means that friction between the splines and the rifle nut and between the chuck and the piston absorbs a high proportion of the available energy on the return stroke. It is important that the sliding parts are well lubricated to minimise the coefficient of friction and to prevent a common cause of wear – the break-up of the splined surfaces.

An advantage of this form of rotation is the absence of any appreciable reaction torque to be sustained by the operator.

Estimation of the torque provided by rifle bar rotation

Refer to Figure 3. The relationship between rotational torque and force on the piston is as follows:

$$\frac{T}{F} = \frac{(r - \mu\pi d_1)\, d_1 d_2}{2\,(\mu r\,[d_1 + d_2] + \pi d_1 d_2 - \mu^2 \pi d_1^2)}$$

where T = the torque available for rotation of the bit
F = the force applied by the air pressure to the piston on the return stroke
d_1 = mean diameter of the rifled splines

d_2 = mean diameter of the straight splines on the chuck
μ = coefficient of friction
r = lead of rifling

This formula is correct for consistent units.

The force F is the product of the area of the piston A_r (Figure 5) and the air pressure P_r. This formula is accurate for consistent units.

As an example of the use of this formula, take a drill with a bore diameter of 66.7 mm in which d_1 = 19.3 mm, d_2 = 34 mm, r = 0.762 m (30 in). Two values of the coefficient of friction can be taken, μ = 0 and 0.2.

For μ = 0,

$$\frac{T}{F} = \frac{r}{2\pi} = 121.3 \text{ mm}$$

For μ = 0.2

$$\frac{T}{F} = 24.3 \text{ mm}$$

A value of μ = 0.2 is fairly typical for lubricated steel surfaces. It may be a little less between the steel rifle bar and the bronze rifle nut.

The return area, A_r, of the chosen drill is 2303 mm^2. The maximum operating pressure of the drill can be taken as 6 bar; whilst this pressure is not realised in the return chamber of the drill during normal operation, it is approached under stall conditions (when the calculation is likely to be of most use).

So the stall torque when μ = 0 is given by:

$$T = 121.3 \times 6 \times 2303 \times 10^{-4} = 168 \text{ N m}$$

and when μ = 0.2,

$$T = 33.58 \text{ N m.}$$

The latter figure has been demonstrated to be experimentally correct for the chosen drill. The calculated values indicate two important points: the importance of reducing friction by supplying adequate and correct lubrication, and the torque available for rotating the drill is comparatively small. Should this value be applied, it will stop the operation of the drill. This can easily occur if the drill bit is allowed to jam in the hole through an accumulation of drilling debris. This is the main reason why, in most modern heavy rig-mounted drills, the rotation mechanism is provided independently of the impact mechanism by a separate motor able to supply much greater torque.

Drilling performance of a percussive rock drill

Figure 6 illustrates the principle of rock drilling. When the piston impacts the end of the drill stem, its kinetic energy is transformed into elastic energy which then passes down the rods as a stress wave until the interface between the bit and the rock is met, whereupon the

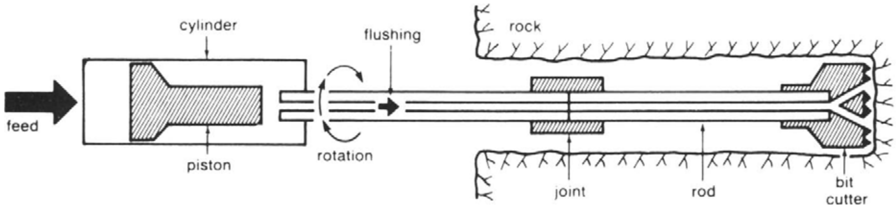
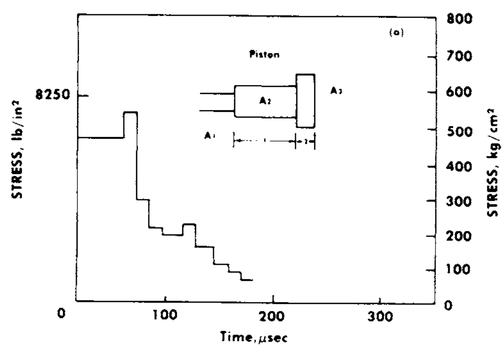


FIGURE 6 – Principle of percussive drilling.

rock fractures. The shape of the stress wave (*ie* the plot of stress magnitude versus time) is an important element in assessing the effectiveness of the drill in breaking rock. The shape can be calculated from considerations of the geometry of the piston and the impact train of drill rod and bit. Its overall magnitude is proportional to the velocity of the piston. The actual calculation of the stress pattern is a complex and time-consuming exercise, which is conveniently solved by a graphical method as described for example in "Down-the-hole drilling using elevated air pressures", M.G. Adamson, Quarry Managers' Journal August 1967. Computer programs are also available to perform the same calculation ("Digital machine computations of the stress waves produced by striker impact in percussive drilling machines", R. Simon, Rock Mechanics, ed. by C. Fairhurst, Pergamon Press).

Figure 7 compares a theoretical calculation with the actual stress pattern measured by a strain gauge.



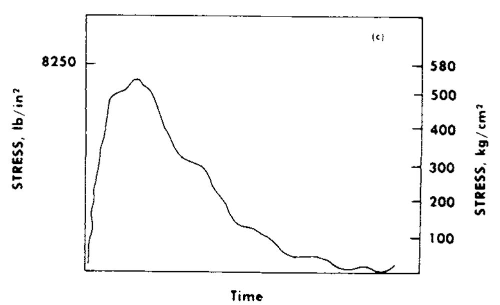


FIGURE 7

The total energy of the stress wave is given by:

$$W = \frac{Ac}{E} \int \sigma^2 \, dt$$

where W = energy content of the stress wave (J)
A = cross-section area of the drill rod (m^2)
c = velocity of sound in the drill (5000 m/s for steel)
E = modulus of elasticity (2×10^5 MN/m^2 for steel)
σ = stress in the drill rod (N/m^2)
t = time (s)

The energy content of the wave can be used to assess the penetration rate of the drill, but it is difficult to relate directly the value of W to the drilling speed, because of the variability of different rocks. Although a number of attempts have been made to define a property of a rock which allows a calculation of its "drillability", none has been entirely successful. There is no substitute for drilling trials in the actual rock.

The stress pattern in the drill stem can also be used to assess the maximum stress that occurs in the elements of the impact train. Most modern drills are limited to an impact velocity of 10 m/s.

The initial stress caused by impact is given by

$$\sigma = \rho \, c \, v$$

where v is the impact velocity of the piston.

If c = 5000 m/s, $\rho = 7.85 \times 10^3$ kg/m^3 (for steel), and v = 10 m/s,

$$\sigma = 7.85 \times 10^3 \times 5000 \times 10 = 393 \text{ MN/m}^2$$

A stress level of this magnitude will be recognised as a very high one for repeated applications and calls for a good quality steel.

A number of specialist manufacturers make drill rods and screwed couplings. A wide variety of different types of thread and couplings are available, the choice is very wide and reference should be made to the manufacturer for recommendations.

Most modern drill bits use a tungsten carbide insert, which can adopt several different forms:

- for small diameter holes a single chisel bit;
- for larger diameter holes a cross or X-shaped bit;
- for the largest sizes, button bits.

Button bits have come into widespread use in recent years, mainly because they require little or no dressing to retain their drilling efficiency, whereas chisel bits require regular sharpening.

MINING AND QUARRYING EQUIPMENT

Many of the tools described under Contractor's Tools are also employed in mining and quarrying, although the emphasis in modern mining is towards the removal and processing of large quantities of rock, for which high powered drilling rigs are required. The principle of rock drilling is the same, whether a hand-held drill or a multi-head drilling rig is used.

Mining is one area where hydraulic drills are offering a real challenge to the former superiority of pneumatic drills because, when the emphasis is on maximising drilling speed, hydraulic power comes into its own. However, a great deal of mining is still done using compressed air for the drilling process, sometimes combined with hydraulic power for support of the drills and for applying feed and rotation forces.

Hand-held rock drills

The small sinker drills discussed in the chapter on Contractor's Tools are occasionally used in mines and quarries, mainly for work such as drilling for secondary blasting. Two other tools, used in considerable numbers are air-leg drills and stopers. These two drills were first used as a stage in the development towards the modern powered support; they take out some of the physical effort that was formerly needed when using a simple sinker drill.

Air-leg or pusher leg drills

An example of a drill of this kind is shown in Figure 1. The drill as shown is basically a standard sinker drill, without the handles and supported by a pneumatic cylinder which, under pressure, is able to support the weight of the rock drill and supply the feed thrust for drilling. The support leg is hinged to the drill body, so there can be any chosen angle between the drill axis and the leg. This drill is used primarily for tunnelling and mine development purposes.

Figure 1 shows the drill in a rather ideal geometric arrangement, where, if the correct pressure is supplied to the leg, the feed force, weight and leg force are in balance. In practice, the geometry changes considerably during the drilling of the round, so that for some of the time the ideal balance cannot be achieved without the operator applying an

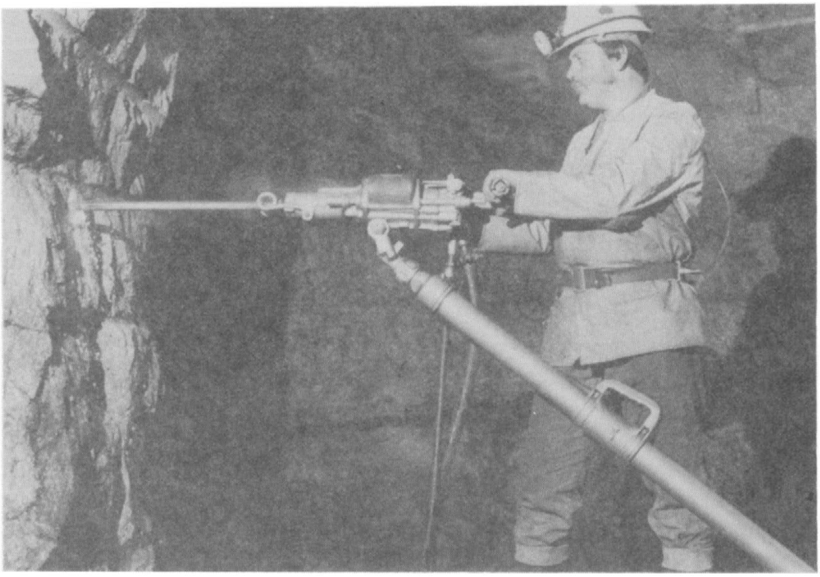


FIGURE 1 – Air-leg drill. *(CompAir Holman)*

extra manual load. When the hole has advanced some distance into the rock, the drill rod itself can give some extra support by bearing against the side of the hole. However, friction against the sides of the hole slows down the rotation and reduces the drilling speed. This kind of drilling requires constant attention from the operator, and also requires a great deal of hard physical effort; in modern, large scale mining and tunnelling it has been largely superseded by techniques using support rigs.

The drill shown is of integrated design, which means that all the controls for drilling and for supplying air to the leg are incorporated in the backhead of the drill. Air passes from the backhead control via passages in the hinge pin to the cylinder. The operator is able to select feed or retract and adjust the feed force from the one control tumbler.

Note that two hoses supply the drill: the larger is for delivering the compressed air; the smaller is for the flushing water, which passes down through the centre of the drill and washes out the rock chippings. Water, rather than air, is universally used for flushing in underground drilling. It has been found that air flushing causes harmful dust to be released into the air, which in the past has been responsible for crippling lung diseases such as silicosis.

Stoper drills

An example of a stoper is shown in Figure 2. This is very similar to the air-leg drill, except that it is designed for overhead work in a stope (a chamber formed for excavating ore) or for drilling a raise (a shaft excavated upwards). The support leg is rigidly attached to the body of the drill and controlled in a similar way to the air-leg drill.

A stoper is also employed for roof bolting (a technique for strengthening a roof in a mine stope by bolting it back into sound rock with long bolts). A stoper intended for rock bolting

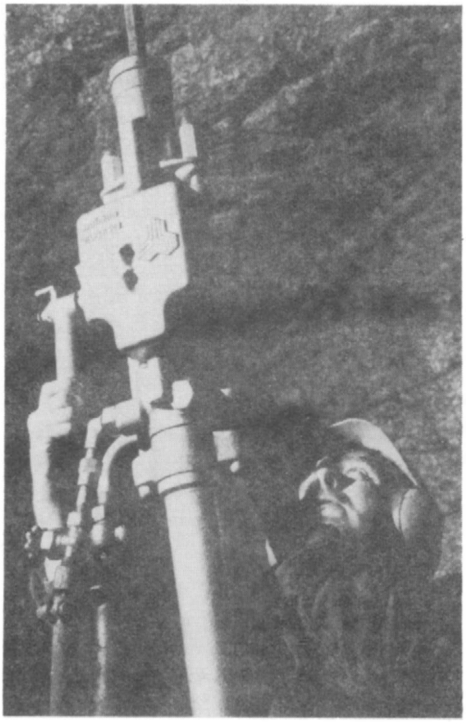


FIGURE 2 – Stoper drill. *(CompAir Holman)*

can be supplied with a clockwise rotation, rather than the more usual anti-clockwise rotation mechanism so that, as well as drilling the hole, it can also tighten the nuts.

Rig mounted drills

Rig mounted pneumatic drills, operating on very much the same principle as the hand-held drills described above are available for underground and surface work.

In recent years, there has been a tendency to move from pneumatic to hydraulic drilling, since hydraulic operation is much more efficient in terms of energy consumption. However, the hydraulic drill is more of a precision tool requiring a higher level of maintenance and the initial cost is higher. The majority of hard rock drilling is still done by pneumatic drills.

Figure 3 shows three drills suitable for this kind of work. In this type of drill the rotation is obtained by a separate rotation motor, which is usually of the meshing gear type. This makes it possible to generate a much higher torque than with the rifle bar rotation discussed in the chapter on Contractor's Tools. The rotation may be separately controlled in speed and direction to meet a variety of drilling conditions. There is also a separate supply of air or water for flushing the hole.

The drill is capable of drilling 100 mm diameter holes several metres in length. The drilling speed depends upon the type of rock drilled and to some extent on the length of

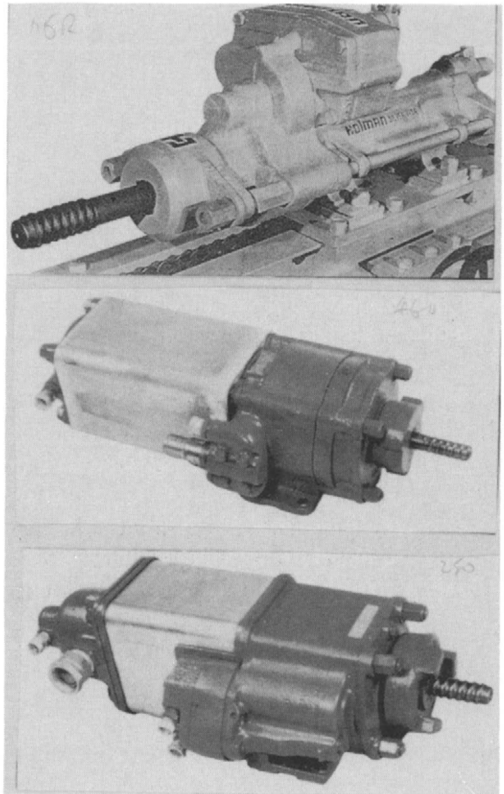


FIGURE 3 – Three pneumatic drills suitable for mounting on a rig.
The top drill is mainly used for surface drilling, the lower two are for underground use.
Air pressure required is 7 bar maximum, air consumption up to 17 m^3/min. *(CompAir Holman)*

the hole. There is always some drop in performance as the length of the drill rod increases. Some of the energy is converted into heat in the material of the drill rod and there are losses at the screwed couplings.

For underground drilling, water flushing is employed to clear out the drill chippings, but for surface drilling, air flushing is more usual. The flushing medium (air or water) passes through a flushing tube situated along the centre line of the drill.

Drilling rigs for underground operations

Support rigs can be comparatively simple as shown in Figure 4, which is a small twin-drill unit on a rubber-tyred base. The motive power is diesel engine, fitted with an exhaust scrubber. This rig incorporates a degree of automatic control on the hole alignment and on the drill control stop and start. One man can easily operate two drills, without any great physical effort.

Large mining operations tend to use multi-drill rigs called jumbos. A jumbo consists of several pneumatic (or hydraulic) drills mounted on a support structure which allows each

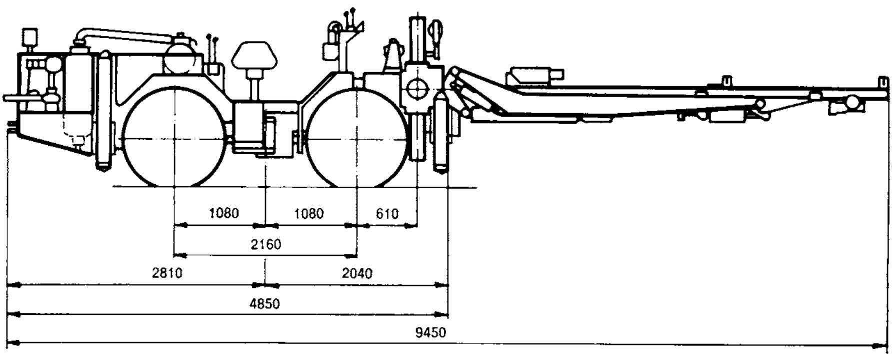


FIGURE 4 *(CompAir Holman)*

drill to be separately controlled from a single operating position. The feed force and the mechanism for positioning the drill at the rock face are usually hydraulically powered. The jumbo itself may be mounted on tyred wheels or on crawler tracks and is self-propelled. The motive power can come from an electric power unit or from an internal combustion engine mounted on the jumbo base. Percussion can be pneumatic (although it has to be admitted that hydraulic is increasingly taking over), with the rotation power coming from a separate pneumatic or hydraulic motor.

With an increasing trend towards automation, control systems for these jumbos become increasingly complex:

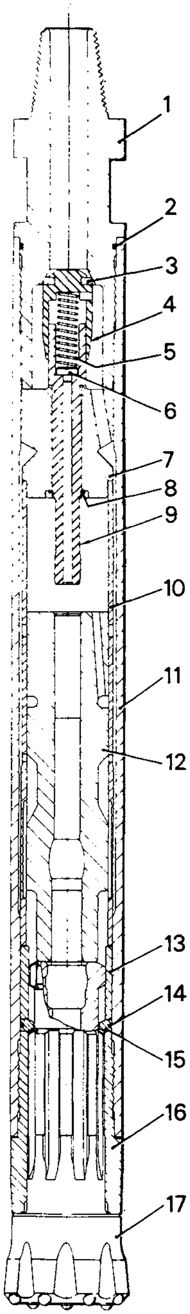
- Feed and rotation power can be monitored and separately controlled to maximise the drilling speed.
- The angular inclination of the holes can be controlled, either for parallel drilling or for a pre-set angle to the tunnel axis.
- A drilling pattern can be programmed into the control unit so that the drill moves automatically from hole to hole to give an ideal blasting pattern.

Quarrying equipment

The drilling regime in a quarry or open pit mine is very different from that in an underground mine, and the drills used reflect that difference. A quarry is required to produce a high volume of rock, produced in "benches" or steps on the vertical (or slightly off the vertical) face of the quarry. The height of these benches can be of the order of 20 m or more, and the diameter of the drilled hole is between 75 mm and 150 mm. With modern equipment it is possible to drill 250 m per man per shift.

In the early quarries, much of the drilling was done with hand-held drills, able to penetrate no more than about 2 – 3 m. Gradually, with the introduction of more powerful rig supported machines and the use of coupled drill rods, the hole depth increased; but it was soon discovered that, when drilling long holes, much of the impact energy was dissipated during its transmission down the rods and through the screwed couplings.

This led to the placing of the drill down the hole close to the bit so that the wastage of energy was reduced.



Item	Component
1	Tube Adaptor
2	O-Ring
3, 4, 5	Non-return Valve
6	Plug (removed for constant blowing)
7, 8, 9	Control Post components
10	Cylinder Liner
11	Cylinder
12	Piston
13	Cylinder Bush
14	O-Ring
15	Retaining Ring
16	Chuck
17	Bit

Method of Operation

The non-return valve ensures that air is trapped in the hammer when the tubes are disconnected, so preventing water and dirt entering via the drill bit.

The bit is locked in by the retaining ring and is released by unscrewing the chuck.

Air enters the tube adaptor at the top of the hammer, passes the non-return valve and is directed into the annulus around the cylinder liner. Air is then directed to each side of the piston by a series of ports, uncovered as the piston moves down the cylinder. Exhaust is controlled by the control post; the exhaust point is reached when the piston passes the end of the control post, allowing the air from the upper chamber to pass through the central hole of the piston and the bit and emerge at the rock face. The return stroke exhaust is controlled by a foot valve which is part of the bit; exhaust point is reached when the striking face of the piston uncovers the end of the foot valve, allowing air to pass through the bit as before.

Extra air can be passed continuously through the hammer to improve hole flushing; this is achieved by drilling a hole in the constant blowing plug, allowing a supply of air to pass directly to the bit, bypassing the power chambers.

The hole can be flushed by lifting the hammer off the bottom of the hole, allowing the bit to drop down against the retaining ring. Air then passes from the return chamber, past the bit splines, which causes the hammering to stop.

The hammer can be supplied with a shock absorber between the tube adaptor and the first tube. This helps to protect the drill tubes and the rotation motor from the reaction forces of drilling.

FIGURE 5 – Components of down-the-hole hammer. *(CompAir Holman)*

These "down-the-hole" drills are designed to produce maximum impact energy in a small diameter body. They have a smooth exterior profile, the bit is locked into the front of the drill, and the rotation is obtained from an external motor connected to the bit by coupled tubes. Because there is no loss of impact energy there is virtually no limit to the hole depth (other than that caused by practical limitations such as tube handling). These drills are universally used for drilling long holes on the surface and, in limited applications, underground. The tubes that support the drill also act as a passage for the compressed air which, after use, is exhausted through the drill bit and is then able to flush away the drill chippings. Such a drill is shown in cross-section in Figure 5.

The drill illustrated is available for bit diameters of 75 to 150 mm and is typical of modern valveless hammers – valveless because air distribution to power and return chambers is achieved by piston position rather than by a distributor valve. Both valved and valveless hammers are available. The valveless type is more favoured for modern drills for two main reasons: they are less subject to clogging by dirt and they are more efficient because the air is used expansively. But different drilling situations require different hammers, so one's choice should be based on a practical drilling trial in the quarry for which it is intended. It will be apparent that the diameter of the hammer, being less than the hole size, is the main factor limiting the design. The impact energy is proportional to piston diameter, stroke length and air pressure; so with the diameter limited, the energy can only be increased by increasing the pressure. Down-the-hole hammers are designed to operate on pressures between 10 and 25 bar for which special high pressure portable compressors are needed.

Support rigs for quarry drills

Choice of a suitable rig for supporting a drill depends on the throughput of the quarry, particularly the number and size of the blast holes. For a small quarry limited by size and

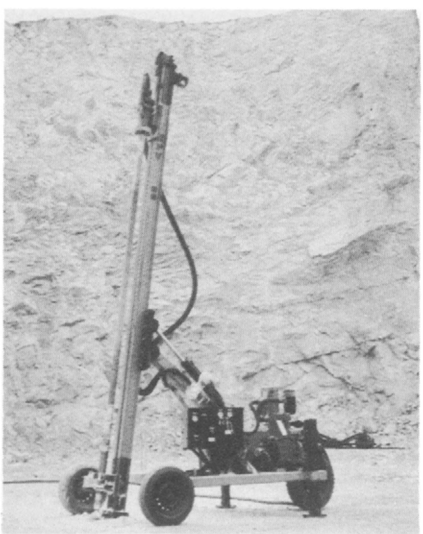


FIGURE 6 – Wagon drill using a down-the-hole hammer. Note the fixed rotation, boom movements and traction are hydraulically operated, with compressed air for the hammer. *(CompAir Holman)*

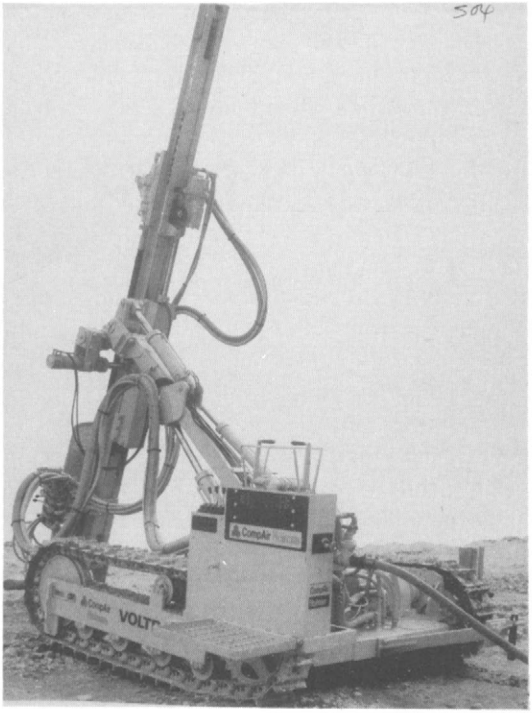


FIGURE 7 – Self-propelled rig for quarry drilling. *(CompAir Holman)*

environmental considerations, the appropriate hole size will be 75 or 100 mm diameter, and a small wagon drill (such as shown in Figure 6) might be appropriate. The drill illustrated is a pneumatic integral rotation drill, with coupled rods. Feed force is supplied by a pneumatic motor driving a chain feed. This rig can also be used for small down-the-hole drilling. This support rig can be equipped with an hydraulic boom for elevating the cradle. Some models can be made self-propelled by mounting a motor on one of the wheels, otherwise it has to be towed from hole to hole by a tractor. The compressor also has to be towed into position.

A more advanced kind of rig is shown in Figure 7; this is a self-propelled tracked vehicle, with the control grouped at a central location. It is shown supporting a down-the-hole drill.

Hole flushing

Good hole flushing is important for removal of the drilling detritus, and can be done either by air or water. Water is customary for underground drilling, where the dust has to be suppressed, but on surface workings where a reliable source of water is not available, dry flushing with compressed air is usual.

With down-the-hole hammers, the exhaust air plays an important role in hole flushing and in most cases is sufficient in quantity for complete flushing, but there is a provision for adding to the volume by incorporating an extra flushing hole, as shown in Figure 5. Most manufacturers of drills recommend a compressor with a capacity about 25% higher than the minimum needed to operate the drill, to allow for extra flushing air. The amount of air required depends on the size of the hole and the diameter of the hammer and rods. After the air has lifted the chippings off the drill face, it is fully expanded and then has to transport the chippings out of the hole. The velocity of the air should be about 30 m/s, calculated from the known volume per second and the annular area between the rods and the hole. If the ground is very wet, with water pouring into the hole from fissures in the rock, the velocity may have to be increased. In good conditions, in hard rock, a lower velocity may be adequate. Too high a velocity is wasteful of air and accelerates the wear of the drill and rods through a "sand-blasting" effect; too low a velocity reduces drilling speed and may cause jamming of the rods.

With water flushing the velocity should be about 1 m/s.

Foam flushing is also used occasionally. It is basically air flushing with the addition of a foaming agent injected into the air inlet. It assists in suppressing dust and lubricating the wall of the hole. It can be a useful technique where dust is a problem and where a dust collector is not suitable.

Dust collectors

A large amount of drilling dust is produced by a high performance drill. Apart from being a health hazard, it is a nuisance to the drill operator and can reduce site safety. Dust collectors have a suction hood which is positioned around the drilled hole to suck away all the dust emitted. The suction is produced either by an air powered ejector or a fan. The dust is carried away through a large diameter hose to the separation equipment which is in two stages. The first stage is a cyclone separator to remove the large particles and the second stage is a filter, which removes the remaining fine dust. Some designs have automatic filter cleaning which comes into action every time the drilling stops; others have to be cleaned after every hole, or when necessary.

AIR MOTORS

General characteristics

Air motors should not be looked upon as a substitute for hydraulic or electric motors. They have their own characteristics which make them ideal in certain applications.

They offer a compact and lightweight source of rotary power, reversible and easily adjustable in speed and torque. They possess characteristics similar to those of d.c. series-wound electric motors.

Air motors can be stalled indefinitely and start immediately with maximum torque. They can be designed to produce equal power in either direction of rotation, merely by reversing the supply and exhaust ports, although maximum efficiency is usually obtainable only when the rotation is uni-directional. They can operate at any speed throughout their design range, and are easily geared to produce maximum power at any required shaft speed. They can be run from any available compressed gas, *eg* from natural or a process gas. They can be run at any attitude.

When comparing pneumatic motors with the alternative using hydraulic or electric power, the following should be borne in mind:

- There is no heat build-up when continuously stalled. When the load is reduced to allow the motor to turn, it will resume normal operation. They can tolerate being driven counter to the applied pressure. The air flow through the motor acts as a self cooler.
- Maintenance is low compared with hydraulic motors.
- There is no sparking, so they are safe in explosive atmospheres. In wet conditions, there is no shock hazard.
- When compared with electric motors they have a higher power/weight ratio (for the same output, the weight is about one-third).
- The moment of inertia is lower than electric and hydraulic motors, so they reach maximum speed quickly and brake instantly.
- They can be installed and operated in any position from horizontal to vertical.

Performance characteristics

All pneumatic motors of any design possess similar theoretical performance characteristics, illustrated in Figure 1. The torque is a maximum at zero speed, although in practice

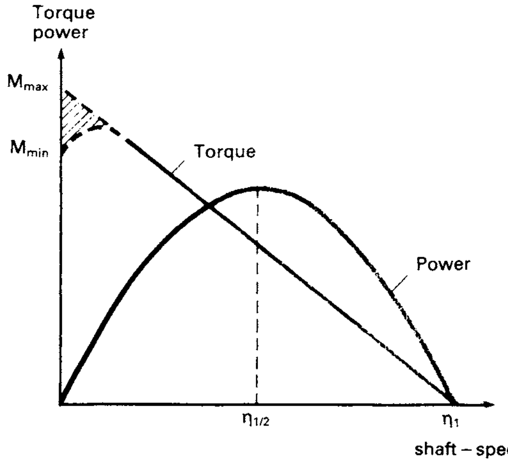


FIGURE 1 – Relationship between power and shaft-speed of an unregulated pneumatic motor.

(as shown in Figure 1), there tends to be a fall-off at stall conditions, caused by break-out friction and by the variable starting position of the vanes or the pistons. Starting torque, (the torque produced by a stationary motor) is about 75% of the stall torque (the maximum torque which will stall the motor), although for some designs it can be as little as 50%. Manufacturers quote minimum and maximum starting torque values, which may differ considerably, according to the starting position of the shaft. If starting torque is an installation parameter, the correct value must be taken. For winches and hoists which may have to start under load, the minimum starting torque is the design criterion; for motors which start off-load, such as for fan drives, the maximum running torque will dominate the choice.

When the motor is stalled, the power is zero. As the speed increases, the torque falls linearly until it reaches zero at its free speed. This linear torque/speed relationship results in the power being a maximum at a speed equal to one-half the free speed. Each curve of this kind is valid for one applied pressure. Where motors are suitable for operation at a variety of inlet pressures, then a family of such curves can be drawn.

One of the important features of air motor behaviour is that maximum power occurs at half free speed.

It is necessary to know the relationship between power and speed before a rational selection can be made of a suitable motor. Most manufacturers of air motors offer a matching range of gear boxes, which allow one motor to be used for a range of speeds. Figure 2 shows how the same motor can be modified to give different characteristics by merely changing the gearing.

These curves are, of course, theoretical; an examination of published curves of commercial motors would show deviations from theory. In particular, most motors are speed limited by some kind of governor, which progressively throttles the air supply as the speed increases. One type of governor is the centrifugal type illustrated in Figure 3. A governor distorts the shape of the high speed end of the power curve, see Figure 4, so as

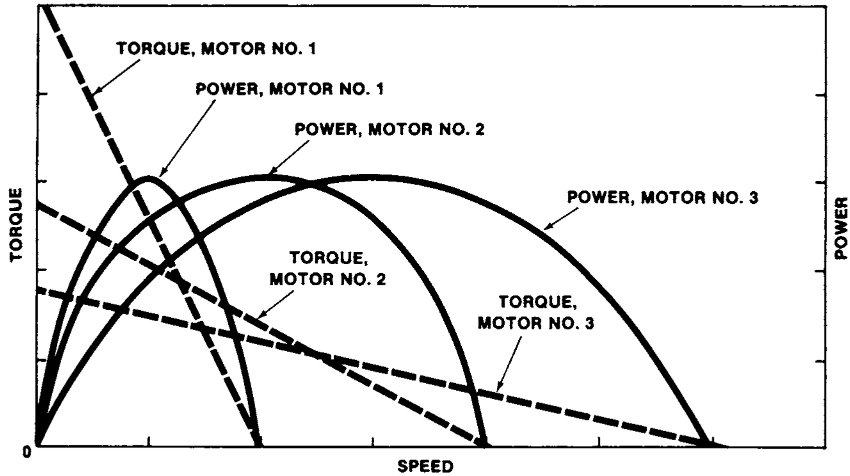


FIGURE 2 – Torque and power for three motors with the same power rating. The curves can be considered to apply to either one motor with different gear ratios or three different motors.

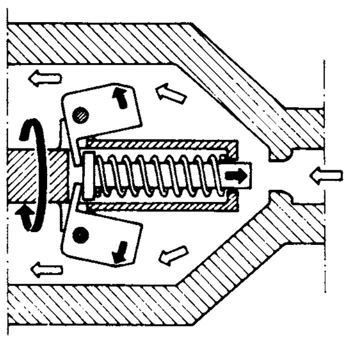


FIGURE 3 – Operating principle of the centrifugal governor.

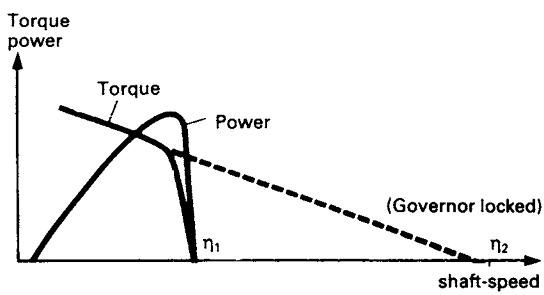
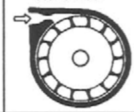


FIGURE 4 – Characteristics of a pneumatic motor with a shaft-speed governor.

TABLE 1 – Survey of characteristics of the most important types of pneumatic motors *(Atlas Copco)*

Type	*Displacement*				*Dynamic*
characteristics	*radial piston*	*piston link*	*vane*	*gear*	*turbine*
					
Maximum working pressure, bar	100	8	8	100	8
Output range, kW	1.5 to 30	1 to 6	0.1 to 18	0.5 to 50	0.01 to 0.2
Maximum shaft-speed, r/min	6000	5000	30 000	15 000	120 000
Specific air consumption, l/kJ = l/(W.s)	15 to 23	20 to 25	25 to 50	30 to 50	30 to 60
Maximum expansion ratio	2:1	1.5:1	1.6:1	1:1	-
Number of cylinders or working spaces per rev.	4 to 6	4	2 to 10	10 to 25	Single-stage
Torque variation during one revolution as percentage of mean value	30 to 15	60 to 40	60 to 2	20 to 10	-
Seal	Piston/ring valve clearance	Piston/ring valve clearance	Gap/positive	Gap/positive	Clearance
Lubrication	Sump and/or air-borne	Air-borne	Air-borne	Air-borne	Only bearing lubrication
Maximum internal relative velocities, m/s	25	20	30	30	70

to limit the maximum speed; it should not affect the peak power. One basic motor can have its characteristics changed by altering the governor weights or spring stiffness.

Table 1 shows the most popular types of motors that are available, with their characteristics.

Vane motors

These motors are similar in concept to vane compressors. Torque is developed by pressure difference on the vanes. There may be between 3 and 10 vanes per motor, but usually 4 or 6. Vanes are usually radial (the centre line of the vane passes through the axis of the motor), but some manufacturers prefer to angle the vanes slightly off the vertical. Vane motors are recommended for high speed operation up to 30 000 r/min. They tend not to be very effective at low speed, because they rely on centrifugal force to seal the periphery of the vanes and without this seal, the pressure cannot be sustained. The air pressure is usually limited to 6 bar in vane motors.

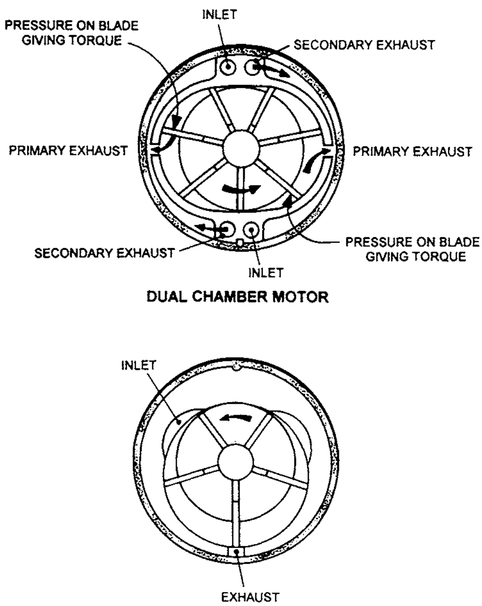


FIGURE 5 – Two configurations for a vane motor. *(Desoutter)*

The more usual vane motor is a single chamber, but it is also possible to make a dual chamber motor. The two are shown in Figure 5. The advantages of a dual chamber are a higher torque at lower operating speeds.

The detailed design of an air motor differs according to whether or not it is intended to be reversible. Reversible operation is achieved by making the inlet port into the exhaust and vice versa; such a design is bound to be a compromise, so rather better efficiencies are available in single direction motors.

The vanes are the vulnerable components of a motor. At very high speed the centrifugal force is so high that frictional forces can cause rapid wear; and at low speed the centrifugal force is too low to ensure sealing contact at all times. If a motor is continuously operated at low speed or under conditions of frequent reversals of direction, the vanes tend to hammer the stator and suffer impact failure. A variety of different materials have been tried for vane manufacture but it has been found that resin-impregnated, fibre-reinforced materials are generally best; carbon reinforced materials are used for heavy duties. The conditions in a motor are quite different from those in a vane compressor, where the speed range is limited, so the same vane materials will not necessarily do. Good air-mist lubrication is essential to reduce friction and wear. The air should be filtered to 64 micron or better. Refer to the manufacturers for recommendations for suitable lubricants. There may be different lubricants specified for the gear-box, the bearings and the oil mist.

Small vane motors are use for hand tools such as drills, grinders and screwdrivers. They

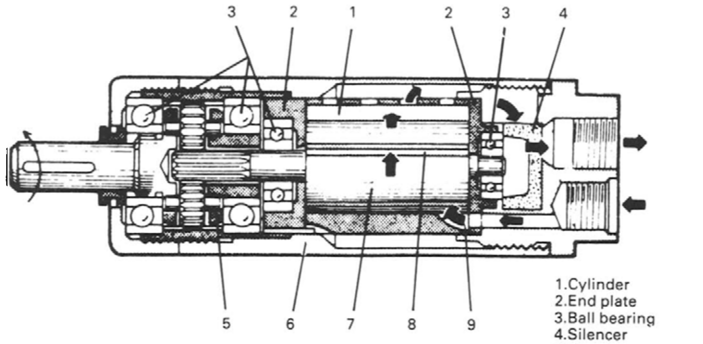


FIGURE 6 – Vane-type air motor.

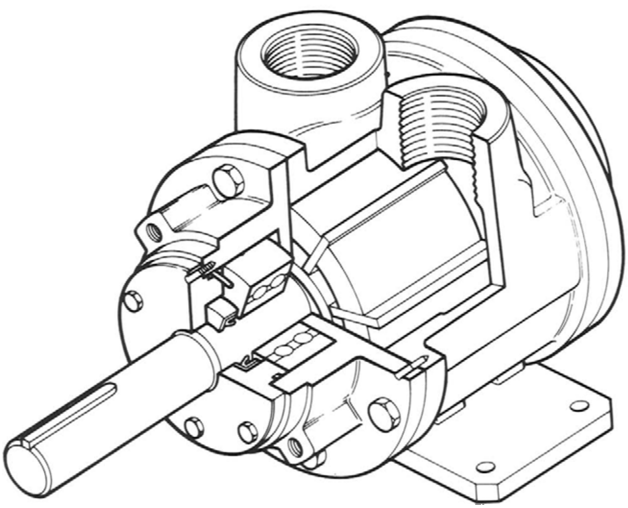


FIGURE 7 – Reversible vane motor for industrial applications. *(Fenner Fluid Power)*

often incorporate a step down gear box in the main casing as in Figure 6. Larger sizes are used for winches, pump drivers, drive motors on pneumatic drill rigs and general industrial applications. Figure 7 shows a large foot-mounted industrial vane motor.

Piston motors

Piston motors operate at lower speeds than vane motors, the limiting factor being the inertia of the reciprocating parts. Free running speed is usually 3000 r/min or less, with the maximum power being developed at 1000 to 2000 r/min.

The majority of piston motors are multi-cylinder units, which may be in-line, vee, H,

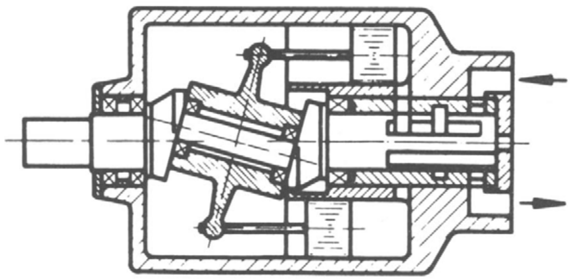


FIGURE 8 – Operating principle of an axial piston motor. *(Atlas Copco)*

flat-four, radial or other variants. In the main, however, the vee is the most popular configuration, with the radial configuration equally popular for three or more cylinders. A radial configuration offers the possibility of weight reduction and is frequently adopted for larger motors. Either an odd or even number of cylinders can used; three-, four-, five- and six-cylinders are commonly found.

The vee-four motor normally has two cylinder banks at 90° to each other. Drop forged two-throw crankshafts are normally used with two connecting rods on each crank pin. Distribution valves may be oscillatory or rotary. Valve timing can be arranged to give equal power in each direction, or may be biased to provide asymmetrical timing and increased speed and power in one direction of rotation.

The typical radial motor has all connecting rods mounted on a common crank as in Figure 8. Power and exhaust strokes are controlled by suitable distribution valves and a two-stage exhaust is often adopted. In this case the inlet valve opens just after top dead centre and remains open for 160°; the inlet valve then closes and a large primary exhaust valve opens quickly to release the air to atmosphere. After a further 40° of rotation, this valve closes and a smaller exhaust valve opens to continue the evacuation of the air.

Reversal of direction of rotation is obtained by interchanging the inlet and secondary exhaust connections, which can be done by means of a control valve some distance away from the motor.

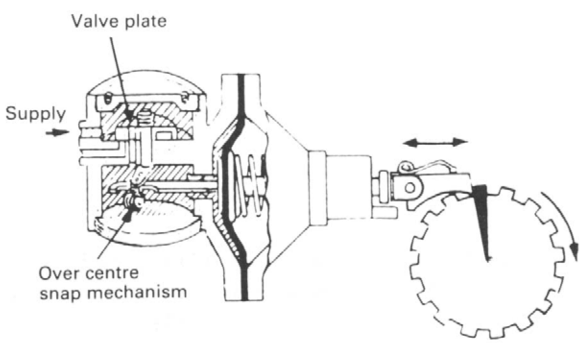


FIGURE 9 – Diaphragm motor. *(Dusterloh)*

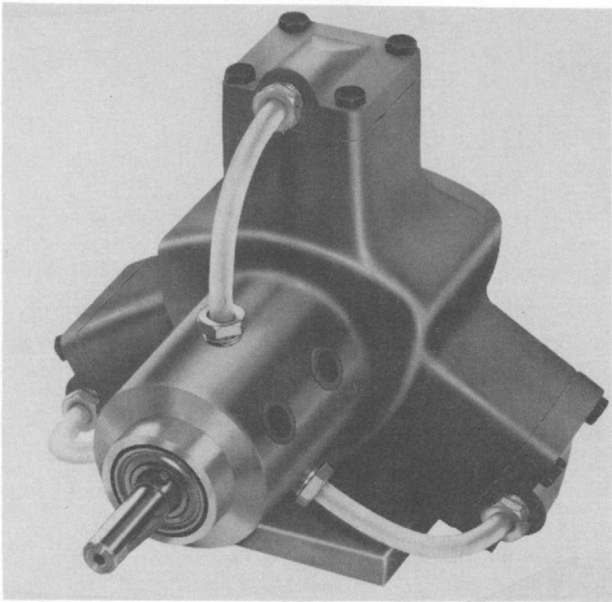


FIGURE 10 – Free piston air motor. Suitable for speeds up to 800 rev/min and a starting torque of 13.5 Nm. *(Dynatork)*

Axial piston motors can have 4, 5 or 6 pistons, but are limited to smaller sizes, less than 2.5 kW. They have the advantage of low inertia, high starting torque and so they reach operating speeds almost instantly. See Figure 9.

Piston motors develop high starting torque, which falls with increasing speed. Both the torque and power are directly dependent on supply air pressure. The torque characteristics can be modified to some extent by detailed design such as the valve timing and valve sizes. They are positive displacement machines, so the air consumption is directly related to speed, within the limitation of the air passages to supply that air. Power output is of the order of 5 to 10 kW/litre of cylinder volume.

Running speeds are generally low to moderate, although small machines may be designed to run at high speeds.

Motors may have output gears to increase the torque and lower the speed.

The overall characteristics of piston motors make them suitable for a wide range of applications. With modification some standard designs can often work satisfactorily down to 0.35 bar. Continuous lubrication is essential and the method of lubrication is dependent upon the design and the need to separate the various lubricants that may be used. A lubricant containing an emulsifying agent may be desirable in a cylinder to prevent water washing, but would not be suitable for splash lubrication in a crank case.

Another variation of piston motors employs a free piston acting on an elliptic cam ring illustrated in Figure 10. The air supply to the cylinder comes from a rotary valve on the main output shaft. Because the design has no need of a connecting rod, the air supply need not be lubricated, which makes it useful for process industries where the presence of oil could not be tolerated. This type of motor is available with either a metal or plastic (acetal) body. It is particularly suitable for low speed applications (up to 800 r/min), and can be driven through a reduction gear box for slow speed process control applications.

Turbine motors

These are very high speed motors capable of generating a small torque only; in the stalled condition the torque is practically negligible. The range of speeds is limited in the range of 50 000 to 80 000 r/min, with the torque a maximum in the mid-range. Applications are limited to those where high speeds with light loads are suitable – high speed pencil grinders and dental drills. Like other air motors a turbine motor can be stalled without damage. Some turbine motors can be fitted with mechanical governors to limit the maximum speed.

Turbine motors operate with clearances throughout, with no sliding or rubbing other than the bearings. Bearing friction is thus the limiting factor governing free speed. Turbines can operate well on dry air – no lubrication other than in the bearings which can be self-lubricating or have their own lubrication system; this can be an advantage in certain applications.

Impulse turbine motors

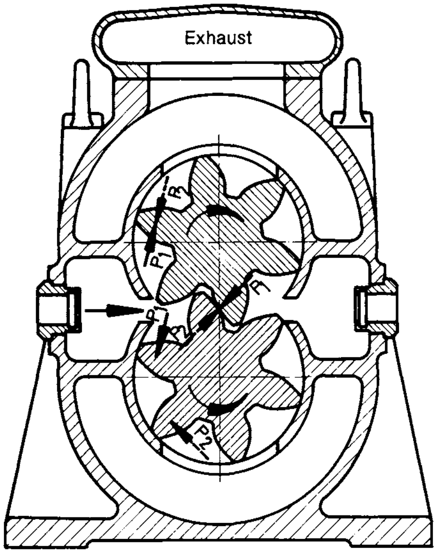
Originally developed in small powers up to 2.25 kW, very much larger turbine motors are now available up to 70 kW. These are normally single-stage impulse turbines coupled to a planetary gear reduction set. They are competitive with vane and piston motors, being smaller and lighter for the same size.

Gear type motors

These motors are based on the meshing together of gears. The simplest and most common type of gear motor is based on a spur gear pair (Figure 11), although other types are available. Helical gear motors have better sealing characteristics and for that reason are claimed to be more efficient in the use of air, but they are more expensive. A helical gear motor having an axial rather than a radial flow path, designed to the same principles as a screw compressor, is likely to be the most efficient of all, but except for special applications its cost will be prohibitive.

Roots motors (similar to the Roots compressor, described in the Compressor chapter) can be included in this category, but they have an inherently high leakage rate and are not normally competitive as motors.

As can be seen from Figure 11, there is little or no expansion of the air between admission and exhaust, compared with the vane or piston type, and this limits the power that can be extracted from the air. In spite of this the spur gear motor is in practice as efficient as a vane or piston motor and, provided that adequate lubrication is supplied with the air, is very robust and has a long life. One advantage of a gear motor is that there is very little variation between minimum and maximum starting torque, which makes it suitable for such applications as starter motors. It is more compact than the radial piston motor and has better low-speed performance than the vane motor.



P_1 is the supply pressure,
P_2 is the exhaust pressure.
Power is generated by P_1 acting on the sides of the teeth.

FIGURE 11 – Mode of operation of gear type motors. The pressure medium enters in the direction of the arrow.

Motor control systems

The simplest control system is a manual on/off valve. For reversible motors a two way spool valve is required, which may be operated either by a simple hand control or remotely. Differential power in forward and reverse directions (as may be required in hoists) can be achieved in three ways:

- through pressure control valves in the supply lines,
- by a biased power spool valve,
- by a restriction in the lines.

A common requirement on air motors is an automatic brake to prevent creep when the air is turned off; it is essential for hoists and winches which have to hold the load safely. Most manufacturers supply the brake as a module, mounted on the output face of the motor. It consists of two spring-applied shoes pressed against a central hub. When air is applied to either of the input ports, a shuttle valve sends air to the brake which overcomes the springs, allowing the motor to turn. See Figure 12.

Gear boxes for air motors

Manufacturers supply gear boxes for industrial motors, either flange or base mounted. One company, for example, offers gear boxes with ratios from 2.3 : 1 to 85 : 1. Gearing may

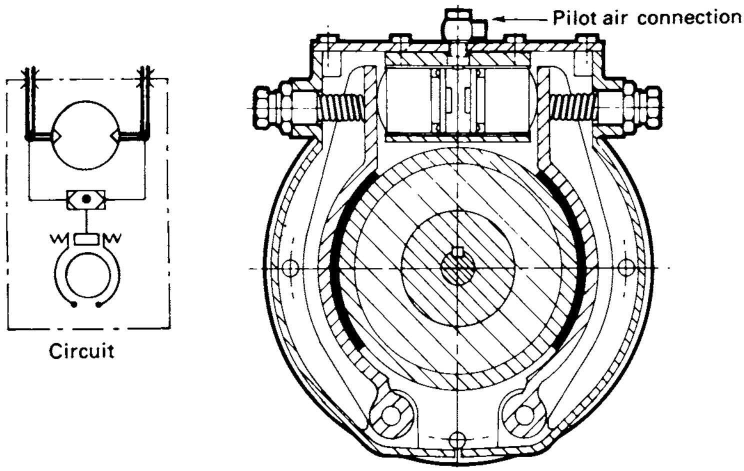


FIGURE 12 – Air motor brake.

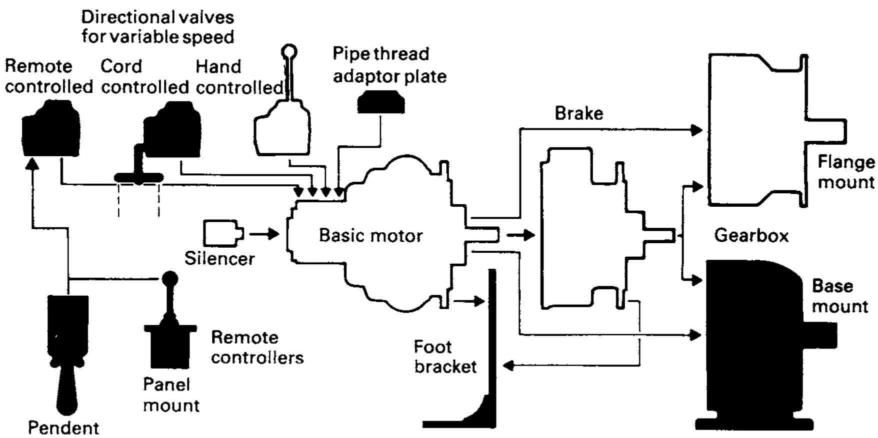


FIGURE 13 – Air motor with a variety of options. Example shows a motor with hand controller valve, gear box, brake and silencer.

be spur, helical, bevel or worm. Figure 13 shows how a basic motor may be supplied with a variety of different controls, brakes and gear boxes. An efficiency of about 85% can be assumed for the gears.

Summary of characteristics of air motors

It will be apparent that air motors are available to meet a variety of applications, and so performance characteristics should be obtained from the manufacturers. From published data on power output, the values of Table 2 have been selected.

The rotational speed at which the maximum power is reached depends on the motor design.

TABLE 2 – Typical power/air consumption values for commercial motors

Motor type	*Power (kW)*	*Relative power (kW per litre/s)*	*Manufacturer*
Vane	1.5	0.039	Atlas Copco
Vane	3.0	0.045	Fenner
Vane	8.0	0.057	Fenner
Radial Piston	2.0	0.055	Atlas Copco
Radial Piston	6.0	0.046	Fenner
Radial Piston	16.0	0.053	Fenner
Free Piston	0.075	0.03	Dynatork
Gear	9.0	0.055	Dusterloh
Gear	66.0	0.059	Dusterloh
Gear (10 bar)	6.5	0.043	Dusterloh
Gear (10 bar)	14.0	0.049	Dusterloh

Motors chosen are a small selection of those available. Pressure 6 bar, except where quoted.

APPLICATIONS FOR AIR MOTORS

Air motors are used in a wide range of applications, such as supplying the motive power for winches, cranes, pumps, dispensing machines, stirrers and agitators. The are to be found in drilling rigs (see the chapter on Mining and Quarrying Equipment), on account of their inherent safety.

They are found in a range of rotary hand tools such as drills, screwdrivers, impact wrenches and grinders where their light weight makes them ideally suitable for continuous manual operation.

Hoists and winches

Lifting and hoisting machines can be powered by either air cylinders or air motors. Pneumatic winches are conventional winching mechanisms powered by air motors, although some types of winching action are also performed by air cylinders.

Air motors or cylinders can be used to advantage where other types of driver are less economic to operate or are excluded because of the conditions involved, for example in high temperatures or in explosive atmospheres. An air motor has the advantage of being simple to control. Motor hoists are equally suitable for fixed installations or for running on an elevated rail.

Cylinder hoists

Cylinder hoists have a more limited field of application than motor hoists when working at extreme or variable heights. Cylinders tend to be more bulky than motors of the same capacity, and need to be able to accommodate the hoist length in the overall length of the cylinder unless double or triple extension cylinders or pulley mechanisms are used.

Cylinder hoists are best suited to fixed installations, although they may be trolley mounted. For particular lifting operations, they have an advantage over air motors in that they can provide greater load stability and a more rigid system.

Air motor hoists

The advantages provided by motor-powered air hoists include:

- small, light weight compact construction
- low maintenance costs

- variable lift speeds
- safe if stalled or overloaded
- continuous operation if required
- suitable for use in explosive atmospheres.

The characteristics of a motor hoist or winch are determined by the type of motor fitted. A piston motor would be used when a high starting torque is required; heavy duty or general purpose hoists are usually fitted with piston motors. Vane motors are used where an economical, compact, light weight unit which does not have frequent stop/start cycles is appropriate.

The basic hoist unit can be equipped in different ways for lifting – wire roller or link chain. Control can be by rope or pendant. Rail-mounted units can also incorporate traction drive to provide traverse motion along a horizontal rail and up gradients. An extension of this is the mounting of the hoist on a wire rope suspended from a safety booth above the working area; the hoist runs up and down the wire rope which can also be swung to one side to provide pick-up over a large area. This form of suspension is limited to smaller capacity hoists with a lifting capacity up to 100 kg. The all-up weight of an air hoist can be as low as 1.5% of its lifting capacity.

Table 1 gives some typical performance data for air hoists.

TABLE 1 – Typical performance data for air hoists

Capacity *tonne*	*Lifting speed loaded* *m/min*	*Air consumption* *litres/metre*	*litre/s*
0.25	18.6	120	40
0.5	12.6	180	40
1	6.3	360	40
2.5	3.2	750	40
5	1.6	1500	40

The free lifting speed (*ie* under no load) is approximately twice the speed under load unless governed. The air consumption, expressed as litres/metre when running free, is about 90% of the consumption under load.

Air winches

The air winch is an efficient device where any force has to be applied by a rope or cable, such as heavy hauling in mines, workshops, shipyards, ships and construction sites. They are available for applying a force up to several tonnes in useful speeds up to about 20 m/min. Winches have either vane or piston motors with a large number of vanes or pistons to give good slow speed performance, particularly a high break-out torque. Normally a winch will incorporate a reduction gear box built into the drum and an automatic spring loaded brake which ensures fail-safe holding when the air control lever is put into the neutral or if there is no air supply. As with all motors, it is essential that the air supply is lubricated and filtered. Remote control is usually available as an option.

Figure 2 shows a typical winch.

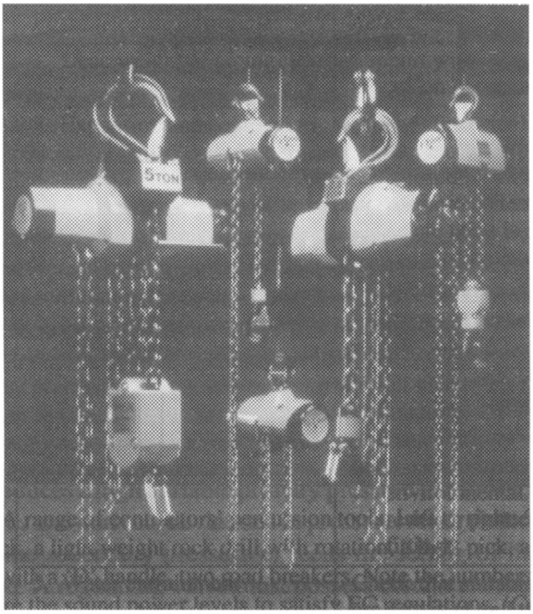


FIGURE 1 – LLA chain hoists. *(Atlas Copco)*

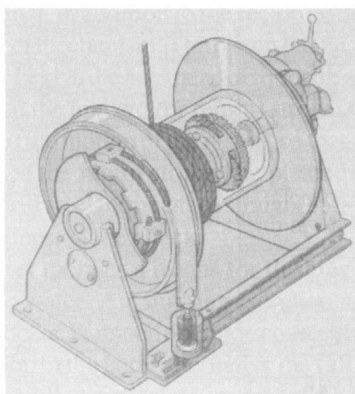


FIGURE 2 – Rope winch. Note the planetary internal gear and the strap type brake. The rope is locked to the drum by clamp jaws and load-relieving turns of the rope.

Compressed air starters

Heavy engines, such as ship's diesels, can be started by direct injection of air into the engine cylinders. The air pressure is usually high (up to 40 bar), so special safety precautions have to be taken, which makes this type of starting system difficult to apply to the smaller type of mobile engine. The compressed air for this application is held in a high pressure reservoir and passes via a distributor valve, which is usually mounted on the engine camshaft, to the correct cylinder. A non-return valve in the cylinder head ensures that there is no return flow after the cylinder has fired. The engine can be brought up to speed very quickly and the system is economical in the use of air.

Apart from this specialist application, when compressed air starting is referred to it means the use of an air motor as an alternative to an electric motor, driving a gear on the flywheel rim.

Air motor starters

Any type of air motor can be used as a starter motor – vane, piston, gear or turbine. Most starter motors have been of the vane type, because they are compact units which can be fitted in the space of an electric starter. Indeed some manufacturers offer a pneumatic starter unit as a bolt-on replacement for an electric motor. In small engines, the meshing of the starter pinion is accomplished in the same way as in an electric starter, with a Bendix drive, *ie* at the commencement of the turning of the motor, the pinion is pushed by a coarse thread into engagement with the rim gear. Figure 1 shows a typical arrangement.

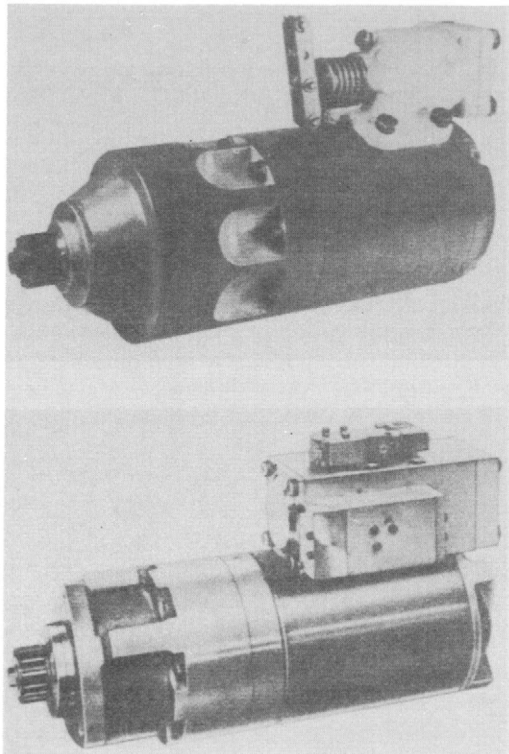


FIGURE 3 – Air starters based on gear type motors. Top figure shows a manually operated starter with an external valve. Bottom figure is an automatic starter with a sensing valve. This design is capable of generating a starting torque up to 330 Nm. *(Dusterloh)*

One disadvantage of the vane motor is that its starting torque is less than its slow-speed running torque, but starting a diesel engine requires maximum torque at its breakaway point. Both gear and piston motors have better starting torque characteristics than a vane motor, and theoretically are more suited to this application.

Air starters have an advantage over electric starters in that the motor can be rotated slowly by admitting air through a small pilot bleed until the gears can mesh. Instead of a Bendix drive, the meshing can be accomplished by an air piston and the disengagement by a spring. The operation can be manually controlled, in which case before the full air supply is admitted to the motor, a visual (or audible) check is needed to confirm engagement of the starter gear. Alternatively for standby sets, where it is required that an engine should start without manual intervention, it can be automatically controlled by means of a sensing valve which ensures that the main air valve does not open until there is complete meshing engagement of the pinion.

Air supply for a starter is typically taken from a reservoir charged by the air brake system on a vehicle or by a separate compressor for shipboard installations. For emergency use, the reservoir can be refilled from a high pressure gas bottle.

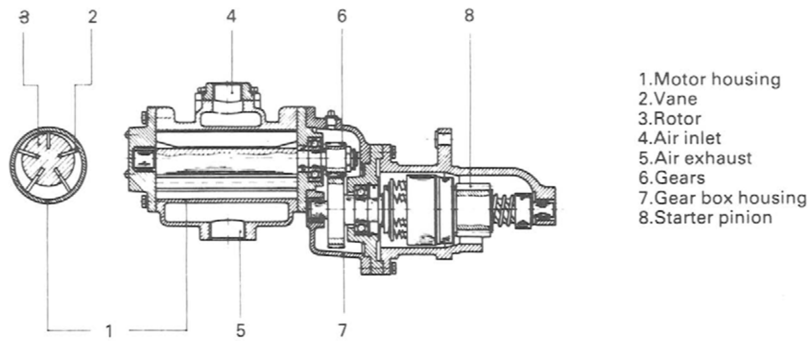


FIGURE 4 – Air starter with vane-type motor drive.

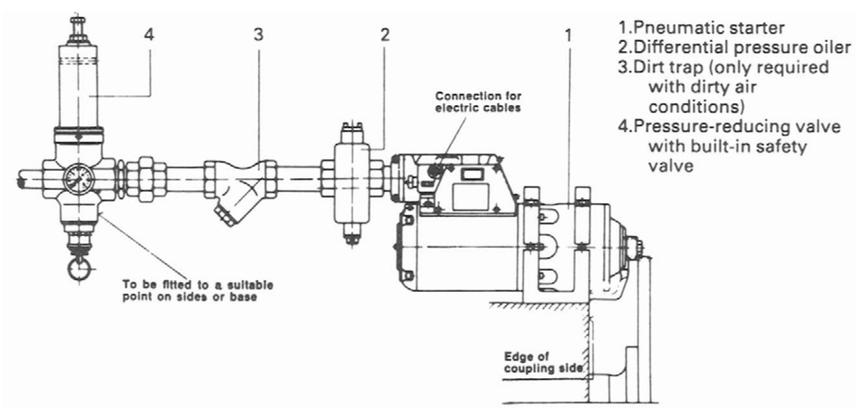


FIGURE 5 – Remote-controlled air starter, saddle-mounted and ancillary parts in the main air supply line.

Air starters compared with electric starters

There are instances when it is an advantage to dispense with electricity on a diesel engine set. There are savings in dispensing with a generator and battery, which are likely to be more than the cost of the air starter and its control equipment. Particularly when the main purpose of running the engine is to drive a compressor, or when compressed air is required for some other purpose, the savings may be considerable.

Air motors are reliable and consistent and generally superior to electric motors in their power/weight ratio. Battery power is much reduced in cold conditions whereas pneumatic motors are unaffected by temperature. If a battery is discovered to be flat, there is little that can be done other than replace it, but an air reservoir can be quickly charged from a source of compressed air.

NOISE FROM PNEUMATIC EQUIPMENT

The general principles of Noise Reduction in compressors have been outlined in an earlier chapter; this chapter deals specifically with tools.

All pneumatic machines and tools tend to produce noise, caused in the main by the discharge of high pressure air from the exhaust port. In addition to the exhaust noise, there may be mechanical noise, particularly from percussive tools.

There is a growing body of legislation limiting the noise from all types of equipment, and this places a duty on both the manufacturer and equipment user. The manufacturer is required to produce a tool which is within the prescribed legal limits, and the employer is obliged to pay attention to the noise exposure of the tool operator by limiting the working time or by providing suitable protection.

In considering the noise generated on a building site, it should be remembered that it is the total noise environment that is important when considering the exposure of the operator or the other site workers. To demonstrate the comparison between tools and compressors, Table 1 has been prepared.

TABLE 1

Machine	*Noise level dB(A)*
3.5 m /min compressor at 7 m	
unsilenced	88
silenced	75
supersilenced	70
Breaker at 7m	
unsilenced	94
muffled	89
muffled with steel damping	88
Breaker at 1m	
unsilenced	106
muffled	101
muffled	100

Unsilenced compressors and road breakers are not available today (at least in the developed world), but the values in the table are useful in indicating the progress of silencing techniques. It can be seen that the breaker is by far the noisier piece of equipment and swamps the noise from the compressor. It makes very little sense to pay for an expensively silenced compressor and use it to operate a noisy breaker. As a general statement, the noise of a compressor can be reduced to any prescribed level, merely by adding progressively better treatment to its enclosure. A compressor can be as bulky as necessary without affecting its functioning; the only drawback is the expense. The same is not true of a breaker, which has to be both efficient and convenient to use. If a breaker cannot be handled, it will not find favour with the operator; so however well silenced it may be, ergonomic considerations will predominate in the choice of a tool.

When trying to reduce the total noise on a site it is clearly desirable to tackle first the most noisy equipment but there may be a practical limit to the noise reduction possible for certain kinds of equipment. The limit appears to have been nearly reached by a modern pneumatic breaker working on a conventional percussion system. Even the use of an hydraulic or electric breaker will not result in a quieter tool – an hydraulic breaker contrary to expectations is just as noisy as a pneumatic one, because most of the residual noise comes from the vibration of the drill bit.

Noise reduction in pneumatic tools

Most tool manufacturers apply some sort of noise reduction treatment to their tools. Figure 1 shows the proportion of noise from the various sources in a road breaker. It can be seen that the first and largest noise source to tackle is the exhaust noise, followed by the ringing noise from the steel, and then the internal clatter of the working parts. Fortunately exhaust noise is reasonably easy to suppress, at least in theory.

The principle to follow is to reduce the velocity of the jet noise from the exhaust port. The pressure ratio at exhaust is as high as 3 to 1, which implies that the exhaust velocity is sonic and the noise is produced by turbulent mixing of the high velocity jet. The theory

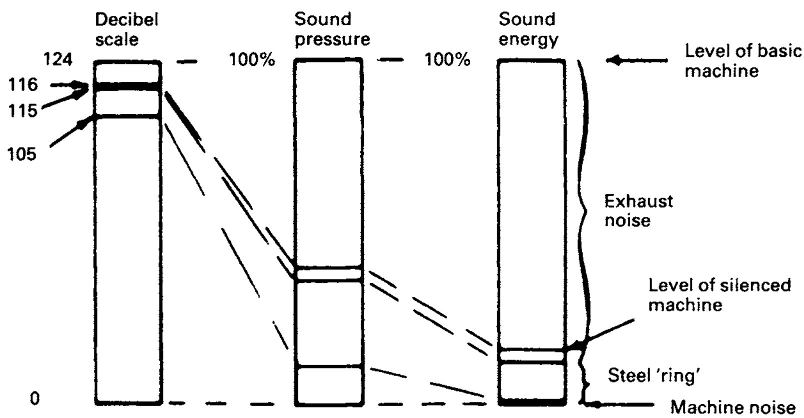


FIGURE 1 – Comparison of the decibel scale with sound pressure and energy for an experimental silenced rock drill.

on which the silencing of engine exhausts is based uses the assumption that the pressure variations are small. Such an assumption is not applicable to pneumatic tools and does not lead to useful designs. The technique that has proved most successful is diffusion of the exhaust stream by a gradually increasing cross section of the air passages. It has to be admitted that much of the design of exhaust mufflers is empirical, and most mufflers have been developed by trial and error. If the only problem were to reduce the exhaust noise, the solution would be easy – it would consist of a succession of expansion volumes joined by restricted passages. However the noise reduction must be achieved without changing the performance of the tool; so there must be no back pressure to impede the motion of the piston and no restrictions in the flow passages which could be clogged by ice formation. Balancing these factors is not easy.

Most manufacturers have found that a flexible plastic such as polyurethane is the most suitable material for manufacture of a muffler. Solid polyurethane is a very robust material which is capable of withstanding hard usage, and ideally it should form an integral part of the tool construction so that it cannot be removed without the tool ceasing to operate. Refer to the chapter on Contractors Tools for a description of the construction.

The next source of noise, particularly in a road breaker, is the steel "ring". As the impact stress wave passes down the tool stem, part of the energy will be absorbed by the road surface, but a proportion of it is reflected back and forth along the length of the tool. The stem is made of a high quality steel and so has a low internal damping, which ensures that it acts as an efficient radiator of noise. Although the energy from this source is small, it occurs at a single frequency and is subjectively very annoying. There have been attempts to suppress the noise from this source by the addition of damping rings to the stem of the tool. Such devices suffered from having a short life and have largely gone out of fashion.

The clatter from the internal working of the tool is reduced by the presence of the muffler itself, particularly if made of a flexible plastic.

The one source of noise which is very difficult to suppress is that produced by vibration of the material being worked. In the case of a road breaker, noise is produced by the shock waves in the road surface. In the case of a chipping hammer or a riveter, noise is generated by vibration of the casting or other component being worked.

Legislation on road breaker noise

Legislation in the European Community limits the sale of pneumatic breakers to those which meet the prescribed noise levels. The EEC Commission Directives, to which reference should be made, are 84/537/EEC and 85/409/EEC. In the U.K. these Directives are implemented by SI 1985:1968 and by the appropriate legislation in other European countries; they quote the maximum levels of noise and the proper test methods to be used. It should be noted that the marketing or use of breakers and compressors (as well as certain other construction equipment) which emit noise in excess of the permitted levels is a criminal offence. Breakers which satisfy the regulations have to bear an approved mark specifying the sound power level (refer to the chapter on Contractor's Tools for an illustration of this). In order to establish conformity with the Directive, the measurements have to be determined at a Test Station approved by the appropriate authority inside the Member Country of the Community. A breaker approved in one country can be freely

TABLE 2 – Approved bodies for pneumatic noise testing

Organisation	*Type Examination for* *Road breakers*	*Compressors*
A V Technology Avtech House Cheadle Heath Stockport SK3 OXU	x	x
Taywood Engineering 345 Ruislip Road Southall UB1 2QX	x	x

imported into another without further inspection. In the U.K., the authority is the Department of Trade and Industry. The laboratories which are able to perform the tests are commercial bodies (rather than Government Laboratories, as in some countries of the Community) and are inspected by NAMAS (National Measurement Accreditation Service). At the present time only the bodies listed in Table 2 are approved to perform tests. They are in commercial competition, so the charge for performing the tests will vary.

It should be understood that the noise level measured according to the Directive is not necessarily typical of the actual noise that is likely to be experienced by an operator of a tool or by a passer-by. The test is performed for type approval of the breaker alone, and so it is devised in such a way that the steel ring and the radiated noise from the concrete block are suppressed. The quoted value is the sound *power* level emitted by the breaker, in the rather artificial test arrangement shown in Figure 2. In order to assess the actual noise exposure in practice, sound pressure measurements should be taken. The type approval test is useful in comparing one breaker with another, but should not be used to determine the noise environment on a particular site.

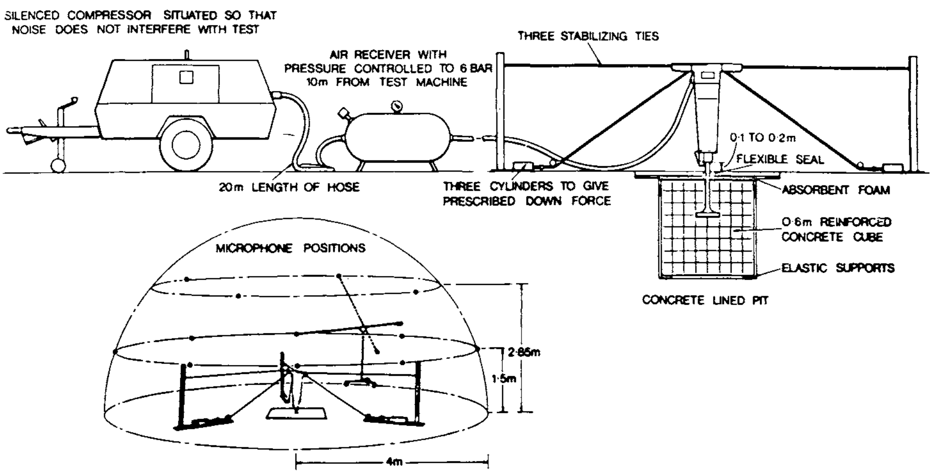


FIGURE 2 – Test arrangement to measure sound power from road breakers according to EEC Test Code. *(CompAir Holman)*

Measurement of noise from tools other than road breakers

So far, road breakers and compressors are the only items of pneumatic equipment subject to legislation. To measure the noise emitted by other items, the only available test procedure is the CAGI-Pneurop Code, which should be studied for further details. This code defines the measurement procedure for all kinds of pneumatic equipment. The readings have to be reported in terms of the sound *pressure* level. The measurement distance from the noise source is 1 m for tools and 7 m for compressors and other large equipment, and the measurement points are situated on the sides of an (assumed) enclosing parallelepiped. This code is useful for assessment of the actual noise experienced by the operator or by the public, since it measures the noise from all sources. It has been shown that when this Code is applied to compressors it gives results (when the sound pressure readings are converted to sound power) that are as accurate as the EEC method. For the reasons given above, this is not the case for road breakers.

TABLE 3 – Permissible sound levels for portable tools

Mass of appliance m in kg	*Permissible sound power level in dB(A)/1 pW*
$m < 20$	108
$20 \leq m \leq 35$	111
$m > 35$ (and devices with an internal combustion engine)	114

Vibration of pneumatic tools

Another health hazard for the user of a percussive tool is vibration. Almost any power tool will generate vibration which, if the level is high enough and the exposure is sustained for long enough, will affect the health of the operator. The main disease caused by vibration is known by a variety of names – Vibration White Fingers, Raynaud's Disease of Occupational Origin or Vibration Syndrome. The Health and Safety Executive prefer the term Hand Arm Vibration Syndrome (HAVS), which includes Vibration White Fingers (VWF). VWF is characterised by intermittent blanching of one or more of the fingers, due to impaired circulation, which gets progressively worse with continued exposure to vibration. There is still much that is unknown about the disease, but the generally accepted view is that it is caused by vibration damage to the peripheral arteries in the fingers; the nerves are also affected. For a discussion on the various methods that are available for the diagnosis of VWF refer to "Hand-Arm Vibration – HS(G)88" published by HSE Books. These methods are not suitable for routine workplace surveillance. Attacks of White Finger are often precipitated by cold. They last about an hour and may be associated with considerable pain as the attack is terminated.

Even if the use of vibrating tools does not result in the disease of White Fingers, the operator may still be adversely affected by the presence of vibration – he is likely to tire earlier and be less effective in his work – so it is sensible to take all reasonable steps to reduce the level of vibration.

Protection of operators from vibration damage

Pneumatic tools which are known to have caused White Fingers include road breakers, riveters, chipping hammers, rock drills and grinders (both hand-held and pedestal). The damage caused by White Fingers is generally considered to be irreversible, so any worker who complains of attacks should be removed from use of vibrating tools and placed in an environment where he is not likely to be subject to cold. Regular checks should be made on those operators who regularly use these tools. Apart from the use of specially designed tools with reduced vibration, the following measures are recommended:

- The tool should be held as lightly as possible consistent with proper control.
- Wearing of gloves to keep warm. Note: there is little evidence that gloves, by themselves, do much to reduce the magnitude of vibration.
- Keep the workshop warm and ensure that operators do not use tools before their hands are properly warm.
- Chisels should be kept sharp and grinding wheels properly dressed.
- Regular periods of rest allow the hands and arms time to recover and circulation to be restored.

Note that there is a recent standard ISO 10819 – Hand Arm Vibration – Methods for the measurement and evaluation of vibration transmission of gloves at the palm of the hand; this can be used to compare gloves, but this is still at a development stage and should be applied with caution.

Acceptable levels of vibration

Several attempts have been made in recent years to assess safe levels of vibration. Any investigation into this subject can only be epidemiological, *ie* vibration injuries and the exposure which causes them can only be assessed after they have occurred; there seems to be no reliable predictive method of determining the chance of an individual sustaining vibration injury.

There are some standards which have been prepared by the International Standards Organisation to which reference should be made. The ISO Standard covering the assessment of human exposure to hand transmitted vibration is ISO 5349 (also BS 6842 and DDENV 25349) which embodies the best current knowledge on vibration exposure. The method of expressing vibration level is by use of a weighted root mean square acceleration which takes into account the whole vibration spectrum. Legislation is not yet in place which specifies maximum vibration levels of a tool, although attention is drawn to the Machinery Directive 89/392/EEC (amended by 91/368/EEC) implemented in the U.K. by The Supply of Machinery (Safety) Regulations 1992 (SI 1992:3073). This Directive requires that the instructions supplied with the tool must state that tests have been done and either the rms acceleration does not exceed 2.5 m/s^2 or if it does, the value must be stated; the test regime under which these measurements are made must be the appropriate one for the tool being tested, see below. Most manufacturers now take 2.5 m/s^2 as a target for vibration levels of their tools.

Figure 3 gives the recommendations of ISO 5349. It should be noted that the sustainable

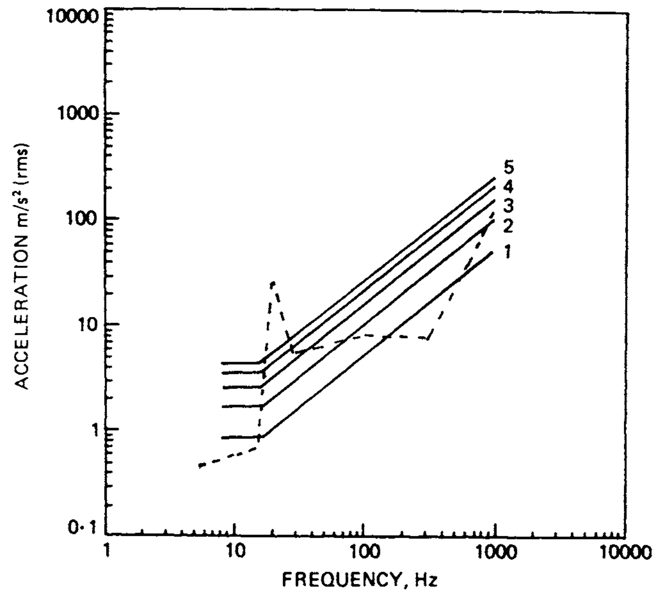


FIGURE 3 – Third-octave hand-arm vibration exposure limits defined in the ISO Standard 5349. The five curves correspond to the five multiplying factors given in Table 4. Superimposed is the vibration level of a typical road breaker. Note the maximum response at the tool operating frequency.

TABLE 4 – Multiplying factors for various exposure durations (as given in the International Standards Organisations Standard 5349)

Exposure time during 8 hour daily shift	*Multiplying factors for various minutes of interruption in vibration exposure per hour*				
	Not regularly interrupted < 10 min/hr	*Regularly interrupted*			
		10 to 20	*20 to 30*	*30 to 40*	*> 40 min/hr*
Up to 30 min	5		–	–	–
30 min to 1 hour	4	–	–	–	–
1 hour to 2 hour	3	3	4	5	5
2 hour to 4 hour	2	2	3	4	5
4 hour to 8 hour	1	1	2	3	4

vibration depends on the amount of exposure during a working day and on the frequency of rest periods. Any recommendations must be provisional in the light of present knowledge on the subject, but most authorities accept the general validity of the data. The standard gives much useful information on the precautions which should be taken to prevent vibration injuries.

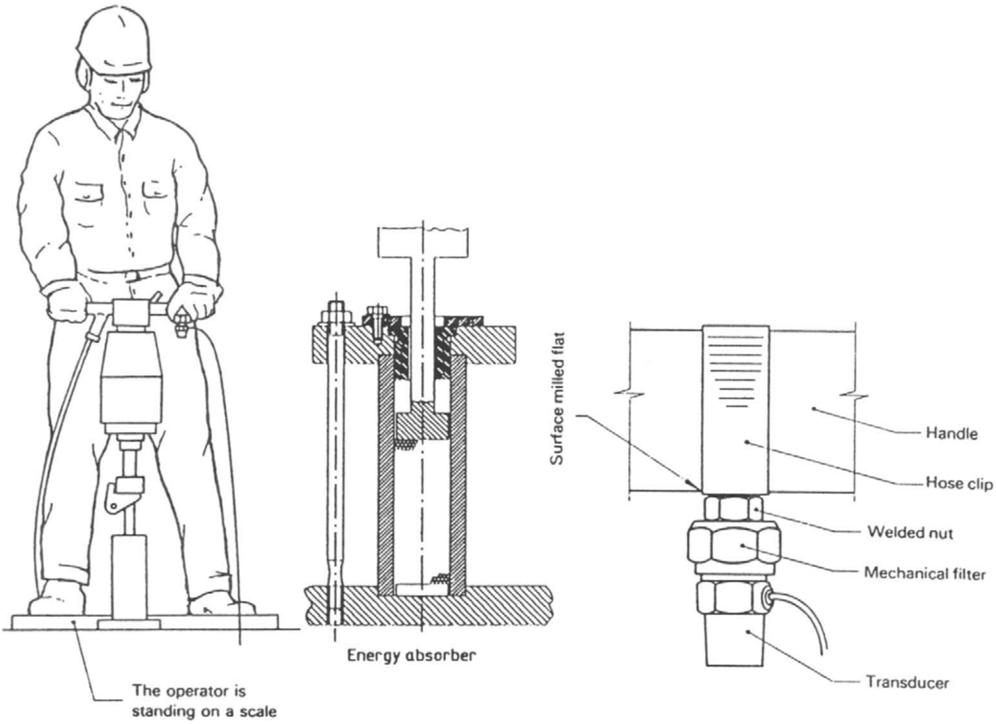


FIGURE 4 – Arrangements for performing vibration tests on a roadbreaker. Note the energy of the impact blow is absorbed by a steel tube 60 mm diameter filled with hardened steel balls of 4 mm diameter.

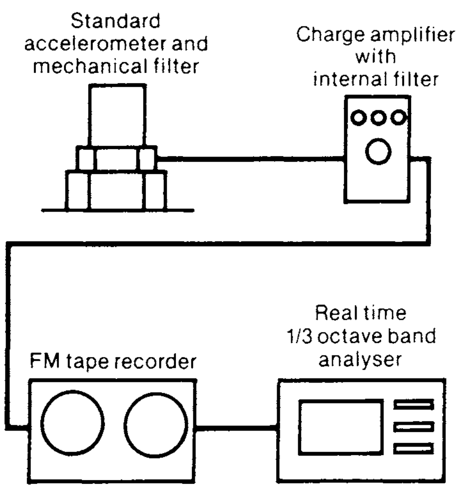


FIGURE 5 – Recommended measurement chain for assessing the vibration of percussive tools.

Measurement of tool vibration

The usefulness of vibration standards necessarily depends on an exact method of determining the vibration of the tools. Standards for the measurement of handle vibrations of percussive tools have been issued for chipping hammers, rivetting hammers, rock drills, rotary hammers, grinding machines, paving breakers, hammers for construction work, impact drills, impact wrenches and orbital sanders, most of which are operated by compressed air. These are to be found in ISO 8662 (BSEN 28662).

There are two fundamental problems in the measurement of vibrations in percussive tools. The first is the establishment of a consistent means of absorbing the energy of the tool. It is not practical to allow the tool to operate in the same way as it would in practice because it would be impossible to ensure consistency; in a road breaker, for example, the variability of the concrete would make comparisons between different testing stations impossible. It might be thought that the energy absorbing method illustrated in Figure 2 would be satisfactory, but this has not been adopted by ISO. Instead the percussive energy is absorbed in a steel tube full of hardened steel balls as illustrated in Figure 4. Tests on this method have shown that the reflected energy from the absorber is of the order of 15 to 20 %, which is typical of a working situation. In ISO 8662-5, detailed dimensions are given for various sizes of tool. The down force, expressed in newtons, to be applied by the operator is to be 15 times the value of the mass of the tool in kilograms; this is in addition to the weight of the tool.

The second problem is the mounting of the accelerometer on the tool handle. Most modern tool handles are covered in resilient handgrips to reduce high frequency vibrations; the attachment of an accelerometer to these is unreliable, so ISO recommend the use of a rigid adaptor clamped to the handles. Mainly through the work done by Pneurop, the correct techniques for vibration measurement have been established and incorporated in ISO 8662. One feature of the vibration spectrum which has to be borne in mind is the high level of shock present which, unless precautions are taken, can seriously affect the accuracy of the readings. Vibration readings of the order of a few metres per second have to be measured in the presence of short-period shocks several thousand times higher.

Pneurop found that the only satisfactory measurement technique is as shown in Figures 4 and 5. A piezo-electric accelerometer is mounted on a mechanical filter which isolates the high shocks (a mechanical filter is a special accelerometer mount, with a rubber insert, which has a flat response well beyond the measurement frequency). The use of so-called shock accelerometers has been found to be ineffective in this application; all the shock accelerometers that have been tried suffer from a phenomenon known as d.c. shift, resulting in false readings. The analysis equipment must be of high quality; an FM recorder should be used, and the amplifier must give indication of signal overload. For further advice on the mounting of accelerometers, refer to ISO 5348 (BS 7129).

The difficulties inherent in the measurement of vibration makes it imperative that any manufacturer or importer of tools must chose a test laboratory familiar with the technique described above. Such a laboratory may be an in-house facility or a commercial company prepared to do the work. There are as yet no laboratories accredited by NAMAS. It appears that the only one currently able to do this work is situated at ISVR Southampton University, although some manufacturers have their own equipment.

Vibration reduced equipment

Some pneumatic tools have been designed with a degree of vibration isolation and their use should be encouraged where they are available. Most manufacturers now supply this kind of equipment.

There are several methods which are used to suppress the vibration of percussive tools; most of the work has been done on the road breaker. Modern tools have comfortably shaped handles, usually made of rubber or plastic or they have resilient grips which help to take out the high frequency "sting". If the grips are removable, they must be regularly inspected and replaced when worn. A rather more elaborate form of the same idea uses spring bushes and hinges to support the handles; an example of these can be found in the chapter on Contractor's Tools.

The predominant low frequency vibration occurs at the operating frequency of the tool and is the hardest to suppress. One method uses spring/mass isolation of the handles; the spring can be a metallic helical spring or it can use the compressed air as a spring. The sprung mass attached to the handles has to be fairly large to give a cut-off frequency at the operating frequency of the tool (about 16 Hz for a road breaker); another method incorporates an internal mass which moves in opposition to the piston, so as to neutralise the external vibration.

These methods can be effective, and a reduction of the order of 90% is realisable, but a word of warning should be given to anyone considering a purchase. Any artificial flexibility introduced into the handle is bound to affect the response of the operator, and while on a test rig the tool may behave very well, it may fail to meet the test of user acceptance. Because of the extra complexity in construction, the tool may be heavier and more expensive. Special tool bits may also be required. The assessment of vibration exposure is a complex matter, depending not only on the magnitude of vibration of the tool handles, but also on other factors such as the grip force. It would make little sense to reduce vibration yet at the same time require the operator to apply a greater force to keep the tool on the work surface.

Other pneumatic tools

Chipping hammers have also been made available with a degree of vibration isolation, see Figure 6. This tool has a piston on which the air pressure constantly acts on its rear surface, so the reaction force on the handle is constant; air is alternately admitted to the front of the piston and exhausted from it; the piston reciprocates under the unbalanced forces. The force in the front chamber acts only on the tool bit, which is not felt by the operator. Shock reflections from the chisel are cushioned by the front collet. This tool is claimed to have a considerable reduction in vibration when compared with a conventional tool.

Hand held grinders also have high vibration levels. As mentioned in the chapter on Industrial Tools, vibration is produced mainly by imbalance of the wheel so it is important to keep the grinding wheel regularly dressed and balanced. In the chapter on Industrial

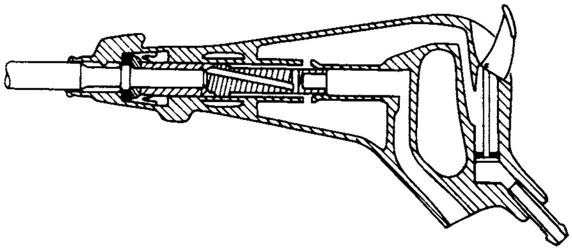


FIGURE 6 – Chipping hammer designed to have minimum vibration. *(Atlas Copco)*

Tools, a grinder is illustrated which incorporates a set of bearing balls which can compensate for imbalance. Fortunately the measurement of acceleration does not the involve the same high shock levels as in percussive tools, so the accelerometer mounting is not as much of a problem.

For further information refer to "Handbook of Noise and Vibration Control" published by Elsevier.

PAINT SPRAYING

There are three basic methods of spray painting: low pressure (the conventional method), high pressure and electrostatic painting. All three can be used for cold or hot spraying. They each have their own particular characteristics, and in order to decide which is the appropriate one for a particular application a number of factors have to be taken into account, such as economy in the use of paint, finish and capacity. Table 1 rates the various methods for suitability. Compressed air is used in each method, and particular care must be taken to ensure that the air is supplied dry and oil-free, if high quality work is required. Air may also be used for preparation of the surface prior to painting. Cleaning off the rust, old paint *etc.*, is done by blast cleaning using shot, steel sand or some other kind of abrasive particle.

Low pressure paint spraying

In this technique compressed air is used both for atomizing the paint and for carrying it to the spray gun. The air pressure used is about 6 bar. Paint is supplied to the gun by one of the three methods illustrated in Figure 1. The choice of method depends on the type and quantity of the paint to be used. For low viscosity paint, suction feed is adequate; gravity and pressure feed are better for higher viscosity paints. The pressure feed method is suitable for large capacity spraying. With suction or gravity feed, the capacity is up to 0.5 litre/min; pressure feed allows up to 2 litre/min. The air consumption varies from 2 litre/s to 10 litre/s according to capacity.

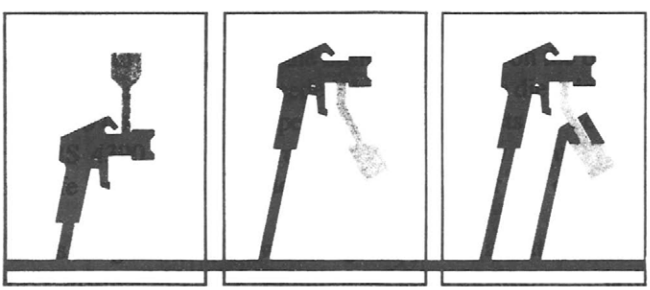


FIGURE 1– Different paint feed. Left: gravity feed. Middle: suction feed. Right: pressure feed.

TABLE 1

Features	*Method of application*							
	Low pressure spraying	*High pressure spraying*	*Hot low pressure*	*Hot high pressure*	*Low pressure electrostatic*	*High pressure electrostatic*	*Hot low pressure electrostatic*	*Hot high pressure electrostatic*
Controllability:								
Fan pattern	4	3	4	3	4	2	4	2
Paint quantity	4	3	4	3	4	2	4	2
Low capacity	4	2	4	3	4	2	4	3
High capacity	3	4	3	4	2	3	2	3
Penetration of paint particles	3	4	3	4	2	3	2	3
Uniformity of coat thickness	3	1	4	2	3	2	4	3
Atomization (finish)	4	1	4	3	3	2	4	3
Wrap-around effect	–	–	–	–	3	2	4	4

4 = very good. 3 = good. 2 = acceptable. 1 = poor.

TABLE 2 – Summary of spray systems

Type	*Characteristics*	*Advantages*	*Disadvantages*	*Applications*
Low pressure (up to 10 bar)	Compressed air used both for paint transport and atomization	Quick and easy adjustment of fan width and paint quantity. Low cost equipment	Heavy paint fog and high paint losses. Limited capacity (2 lit/min max with pressurised feed	Car bodies, office machines, refrigerators, furniture, high class work; spraying primers
High pressure (up to 360 bar)	Necessary pressure generated by a piston pump	High capacity; thicker coatings; minimal paint mist. Suitable for high viscosity paints	Higher cost equipment, less control of finish	Painting large objects, ships, buildings, etc; applying protective plastic coatings
Electrostatic	Can use either liquid or powder paints	Particularly suitable for automated systems; wrap-around coating characteristics. Superior paint economy	High voltage equipment; objects must be earthed; more stringent safety regulations	Car bodies, steel tube items, cycle frames, fences, *etc*

TABLE 3 – Suitability for various types of paints and finishes

Type of paint or finish	*System(s)*	*Remarks*
Solvent type (drying by solvent evaporation)	Low pressure spray High pressure spray Electrostatic spray	Cold or hot spraying as applicable. (Dispersion-type paints are not sprayed) Chlorinated rubber paints may not be suitable for spraying
Air drying by oxidation	Brush painting preferred	
Evaporation and chemical reaction type	Low pressure spray High pressure spray Electrostatic spray	Electrostatic spraying limited to special paints
Stoving enamels	(i) Low pressure spray (ii) High pressure spray	(i) Hot or cold (ii) Hot Electrostatic spraying not generally suitable
Bituminous paints	Low pressure spray High pressure spray	Hot spraying preferred Hot spraying preferred
High zinc paints (organic)	Low pressure spray High pressure spray	Zinc-epozy paints may also be sprayed electrostatically Zinc-epoxy paints may also be sprayed electrostatically
High zinc paints (inorganic)	High pressure spray	

The flow rate and spray pattern is controlled by the needle valve in the spray gun. The paint is atomized by the air passing through the nozzle with the result that a mist of paint particles is present in the spray booth, which can be wasteful in the use of paint, particularly when painting open structures such as bicycle frames. The method is used for automobiles, kitchen machines and furniture.

High pressure paint spraying

This method relies on a high pressure pump to supply the paint to the gun. No air is employed to atomize the paint nor does any air issue from the gun, so the method is also known as "airless" spray painting. Air at 6 bar is supplied to the pump which generates a spray pressure up to 360 bar. The air consumption per litre of paint is lower than with low pressure painting.

The paint passes through a tungsten carbide nozzle with a small orifice and is atomized by the high pressure. Because no air is used at the nozzle, there is little or no mist created. Thick coats of high viscosity paint can be applied, so it is suitable for high capacity applications on large structures, ships and buildings. Up to 5 litres/min can be applied.

Electrostatic spraying

A drawback of both high and low pressure spraying is the wastage of paint when spraying open structures and small components. In electrostatic spraying, the method of atomizing and delivering the paint is the same as with either of the two methods described but, in addition, an electrostatic field of 50 to 100 kV is created between the paint and the sprayed object. The paint droplets follow the lines of the charge field, so it is possible to achieve "wrap-around", as shown in Figure 2, and obtain adequate coverage by spraying from one side only.

This method is useful for car bodies, bicycles and small objects; the coat thickness is even and of high quality, which is difficult to achieve on small objects with the other methods.

It is economical in the use of paint, and there are other savings such as lower cleaning costs.

The operator, spray equipment and workpiece are earthed and the paint is electrostatically charged in the gun. Safety is important with this method, so all the safety precautions must be observed; conductive footwear must be worn.

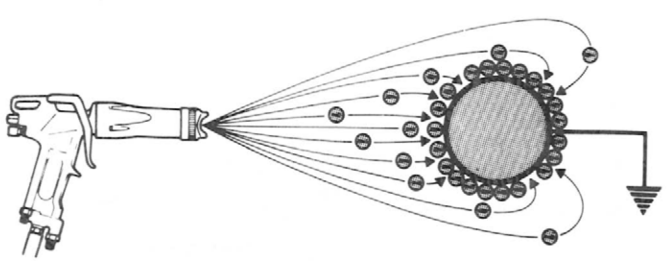


FIGURE 2– Principle of electrostatic painting.

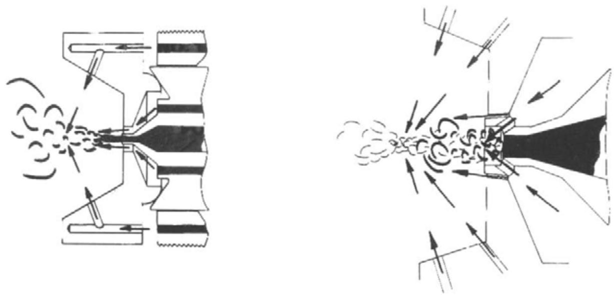


FIGURE 3 – Design of spray nozzle for low pressure spraying. On left, conventional nozzle. On right, improved nozzle showing low pressure mixing regime. *(Kompex Industrial Products)*

Cold or hot spray

Hot spraying allows a paint to be sprayed in a more concentrated form, flows better and produces a more homogeneous coating; it also results in better economy. Hot spraying is particularly suited to the application of thicker coats so is often preferred for priming coats. Low pressure hot spraying is the preferred choice for high quality,gloss finish coats.

Recent developments in the design of spray nozzles has, however, improved the quality of low pressure spraying so that the quality is claimed to be as good as with high pressure systems. The nozzles are designed to work with comparatively low pressure (up to 2.5 bar) and improve the atomization of the paint to produce not only a better finish but less wastage and consequently lower emission of fumes. The design of the new nozzle is shown in Figure 3.

The operating principle for hot spraying is illustrated in Figure 4. Paint is held in a heated container, using either direct or indirect heating. When spraying is not in progress, it circulates in a closed circuit through the pump, heater, and spray gun back to the suction

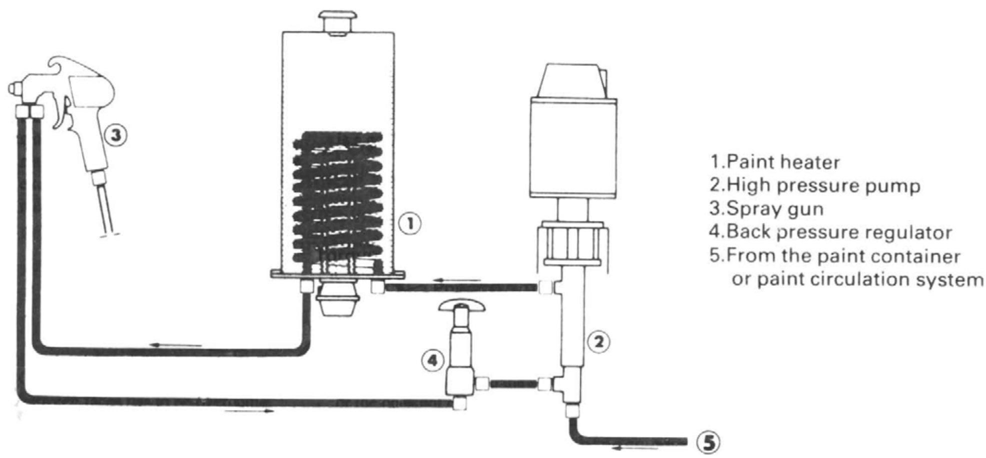


FIGURE 4 – Operating principles for hot high pressure spraying.

side of the pump. A back pressure regulator is used to adjust the paint quality returned to the main circuit.

Paint transport and feed

The paint feed alternatives shown in Figure 1 can be considered as batch feed systems: the paint pot has to be refilled when empty, thus the process is discontinuous. A continuous paint feed system is illustrated in Figure 5. A pressure-operated circulation pump supplies paint to several guns through a ring main. There can be different spray systems on the same line, or the main can incorporate a heater.

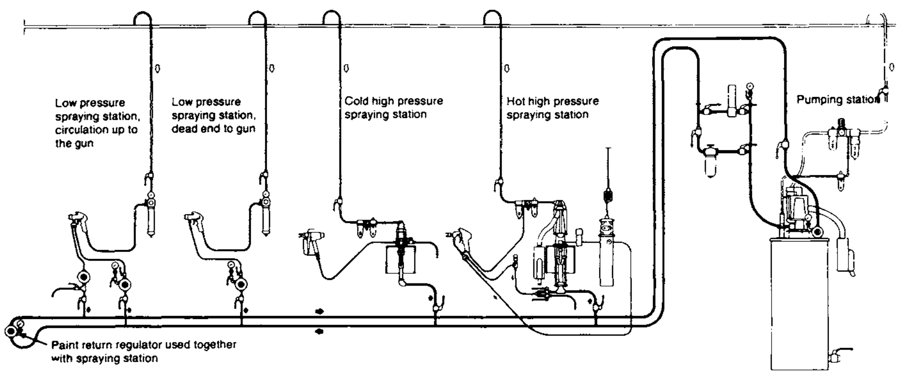


FIGURE 5 – Various circulation systems.

AIR SPRINGS

Pneumatic cylinders as air springs

The air in a closed chamber can be used in much the same way as a metallic spring, *i.e.* it can be used to resist deflection by the compression of the air. The air spring has its own characteristics which differ in some important respects from the metallic spring. It can be used as an alternative to mechanical springs for suspension and for vibration isolation. The simplest form of mechanical spring is the closed pneumatic cylinder, Figure 1.

In all applications concerning air compression, the behaviour depends on the nature of the compression cycle. For very slow speed movements, the compression can be considered to be isothermal, but for high frequency suspension systems the cycle is isentropic (no heat transfer to the surroundings). The following analysis is based on an assumed isentropic cycle, with γ, the index of compression equal to 1.4.

The spring of Figure 1 is assumed to contain an initial air pressure, P_1, which acts in the same way as a pre-load, F_1, in a mechanical spring. When the pre-load is taken up, the

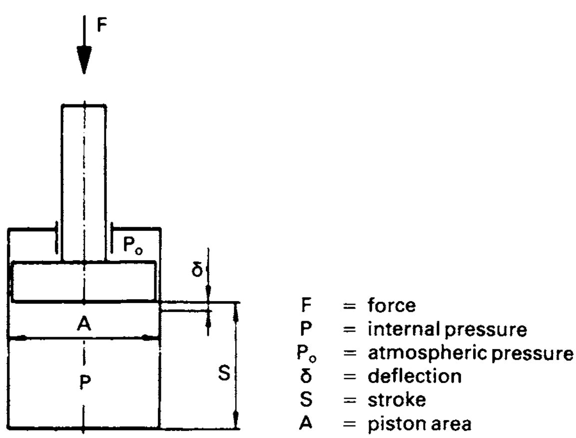


FIGURE 1

spring then has an elastic spring rate which, because of the nature of the compression, is non-linear.

$$F_l = (P_l - P_0)\,A$$

For F greater than F_l, the relationship between F and the deflection δ is given by:

$$F = PA\left(\frac{S}{S-\delta}\right)^{\gamma} - P_0A$$

and the equivalent spring rate is then given by

$$k = \frac{\gamma P A}{S-\delta}\left(\frac{S}{S-\delta}\right)^{\gamma}$$

When a spring is used for vibration isolation (a common application), the natural frequency is given by

$$f = 2\pi\sqrt{\left(\frac{k}{M}\right)}$$

where M is the supported mass

The above formulae are correct for consistent units. With F in newtons, p in bar, A, S and δ in metres and M in kg, the corresponding relations are:

$$F = 10^5\,(p_l - p_0)\,A \qquad \text{N}$$

$$F = 10^5 pA\left(\frac{S}{S-\delta}\right)^{\gamma} - p_0A \qquad \text{N}$$

$$k = 10^5\gamma\,\frac{pA}{S-\delta}\left(\frac{S}{S-\delta}\right)^{\gamma} \qquad \text{N/m}$$

$$f = 2\pi\sqrt{\frac{k}{M}} \qquad \text{Hz}$$

In the above analysis, no account has been taken of seal friction, which can modify the relationships but is practically impossible to analyse. The main limitation to the use of pneumatic cylinders as vibration isolators is their reliance on elastomer seals, which are prone to wear and which cause friction. They are, however, useful for applications where a tension or a double acting spring is required.

The performance of a pneumatic spring can be modified by connecting the cylinders to a suitable external circuit as shown in Figures 2 and 3.

Gas springs are commercially available (Figure 4). These are primarily used for supporting horizontally hinged doors, but are also used for machine guards, hood supports and safety doors. They are filled with high pressure nitrogen rather than air and are heavily damped by hydraulic means. They are sealed units, factory set for the desired force characteristics, available for a maximum force up to 20 kN. For design characteristics refer to the manufacturer.

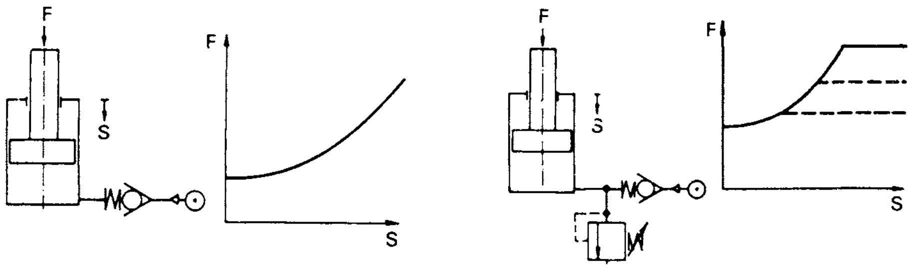


FIGURE 2 – Spring force diagrams – cylinder with non-return valve (left) and with relief valve limiting spring force (right).

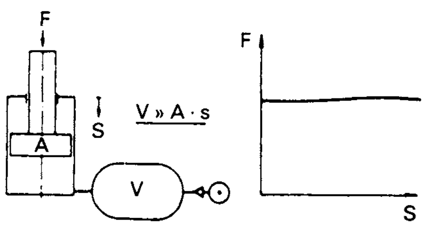


FIGURE 3 – Force diagram with air spring connected to a large reservoir.

FIGURE 4 – Hydro pneumatic gas springs. *(Ace Controls)*

Flexible bellows

The advantages of the flexible bellows type of air spring, Figures 5 to 8, make them very versatile devices, applicable to both actuation and vibration isolation. The standard bellows has a two-ply construction of reinforced rubber with a maximum working pressure of 7 bar; four-ply construction is also available with a maximum pressure of 12 bar. A maximum force of 45 kN and stroke capability of 350 mm are possible. Special formulations of rubber allow low and high temperature operation (from -50°C to 110°C).

As actuators they can usefully replace conventional rams in short-stroke, high-force compression applications. Advantages include:

- no dynamic seal so no breakout friction,
- ability to stroke through an arc,
- ability to accommodate angular and side loads,
- low maintenance and generally lower cost,
- freedom from fatigue.

The force generated by any air spring depends on the pressure and the effective area. A cylinder has a constant area, but the effective area of a bellows changes as it extends. The force is greatest when the spring is collapsed and lessens as it extends; the variation can be as much as 50%.

As isolators, they have a substantially lower spring rate than a similarly sized rubber or steel coil item, allowing system natural frequencies as low as 1 Hz or lower, if an additional

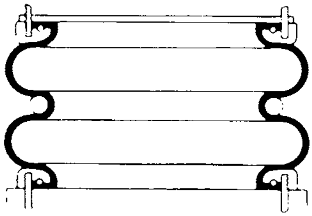


FIGURE 5

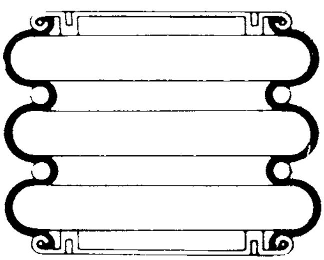


FIGURE 6

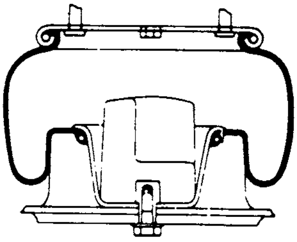


FIGURE 7

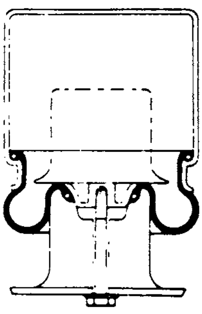


FIGURE 8

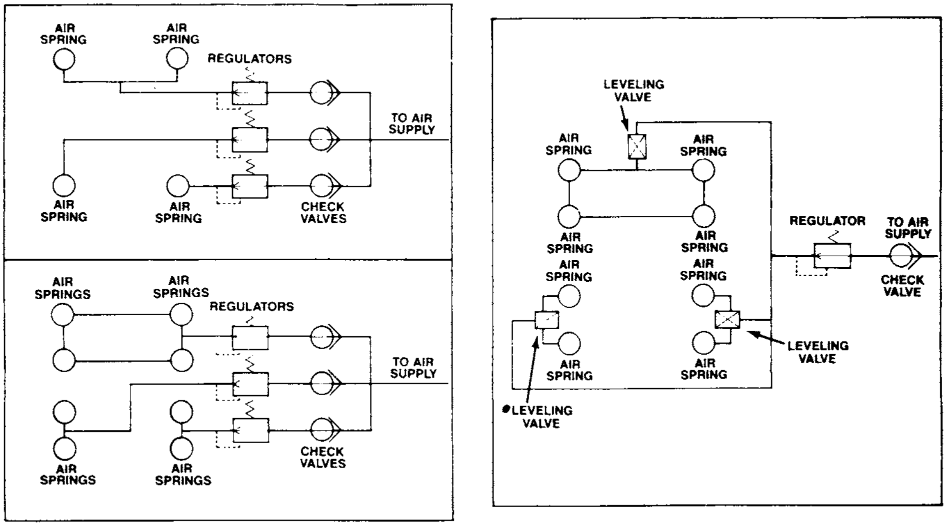


FIGURE 9 – Typical circuits for air supply to an air spring isolator.
Note that in each case there is only a three point control.

reservoir is provided as in Figure 3. They eliminate problems like fatigue and permanent set found in other isolators. The height of air spring isolators can be accurately controlled by regulating the air pressure. With a simple feedback device, such as a levelling valve, the height can be accurately controlled to ± 1 cm; with precision controllers, the height can be maintained to ± 0.25 mm. The air supply circuit needs careful consideration. If the air is sealed in the bellows with an inflation valve, there will be some leakage through permeation over a period of time (a loss of 2 bar a year is typical), so the pressure needs to be regularly checked. Otherwise a live pressure supply must be provided either to each spring individually or to groups of springs, as shown in Figure 9. The principle to follow is that there should be only three points of control on each structure.

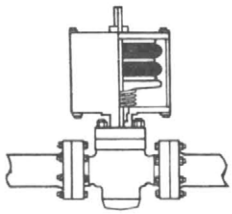
Design Techniques when Using Bellows

Bellows are available in a wide range of sizes and configurations. Maximum diameters vary between 150 mm and 700 mm, in the styles shown in Figures 5 to 8. Up to three convolutions are available as a single unit which can be extended by bolting several units together in series with an intermediate steel plate. Suppliers of these units provide curves which enable the static volume/height and the force/pressure relationships to be determined for each style. When designing an actuator system, it is better to rely on these curves than to attempt to work from basic principles.

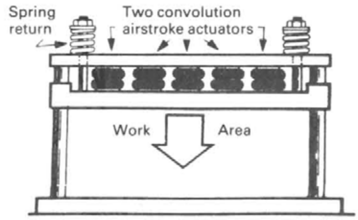
When used as an isolator, the static curves can be used as the primary information from which to calculate the dynamic spring rate. As in the case of the cylinder discussed above, isentropic compression can be assumed (*i.e.* the use of an index of compression = 1.4), although a value = 1.38 is recommended by one major manufacturer; the difference is likely to be small.

TABLE 1 – Air bellows – typical application. *(Firestone)*

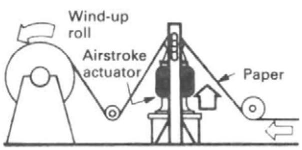
GATE VALVE OPERATOR



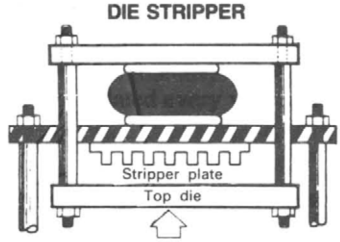
GLUING PRESS



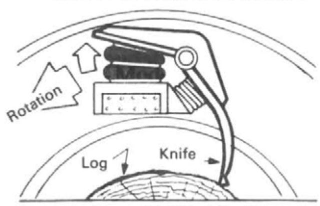
WEBB TENSIONING DEVICE



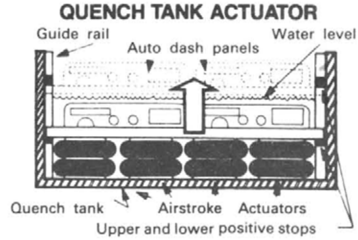
DIE STRIPPER



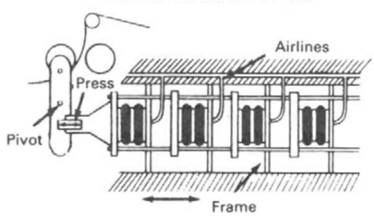
KNIFE SPRING ACTUATOR



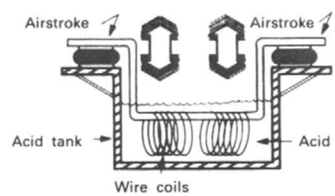
QUENCH TANK ACTUATOR



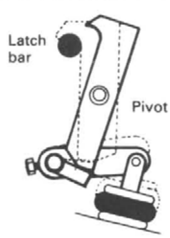
PAPER SIZING PRESS



PICKLING TANK ACTUATOR



QUICK LOCK DEVICE



PRESSURE ROLL FOR CALENDER

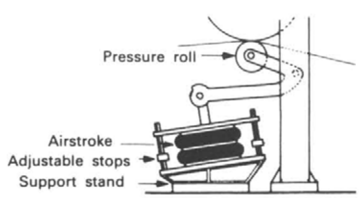
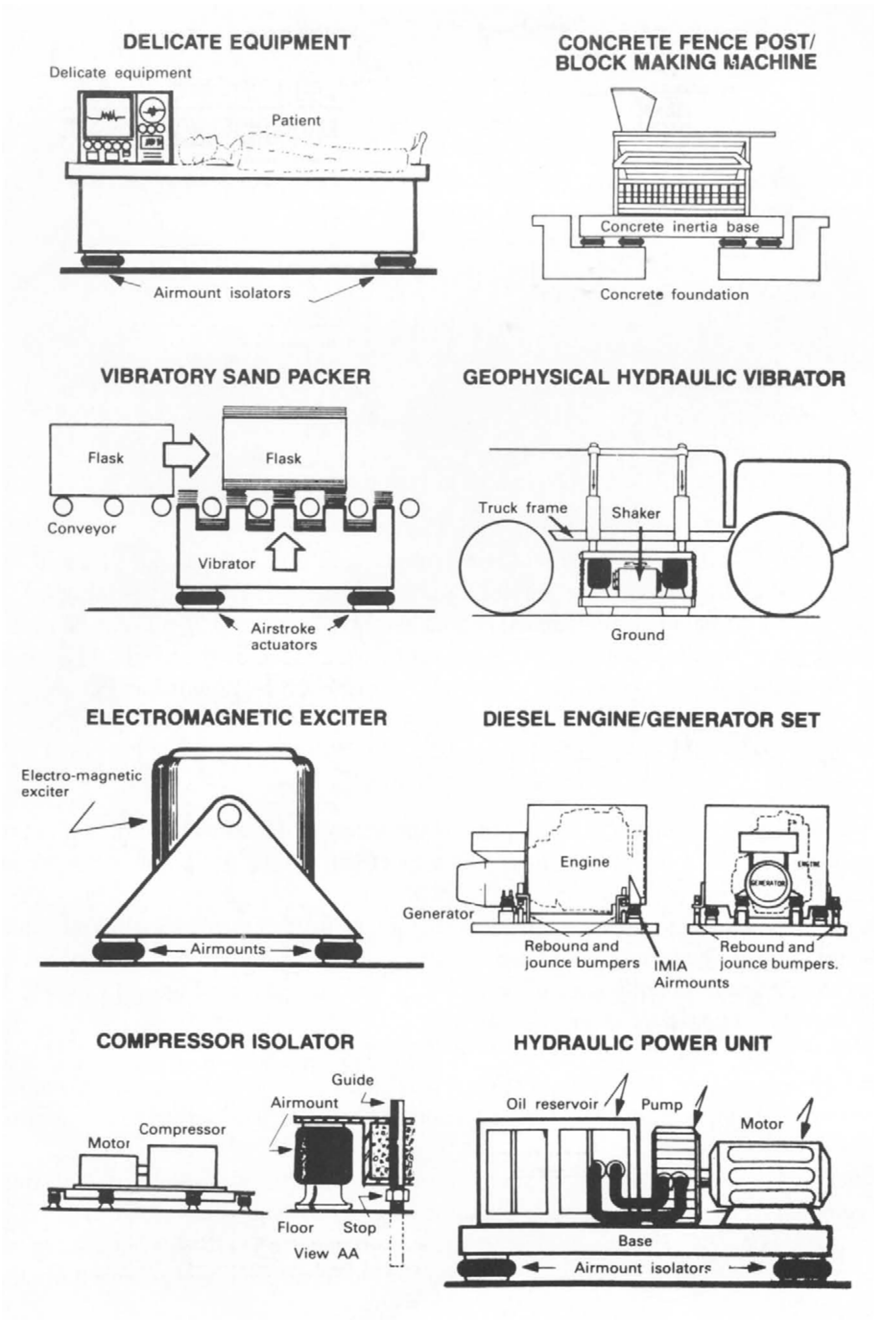


TABLE 2 – Air bellows used as isolators. *(Firestone)*



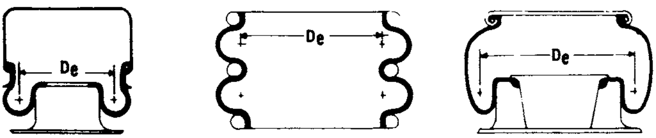


FIGURE 10

In a similar way to a cylinder, the forces can be calculated, but account has to be taken of the variation in the effective area, as shown in Figure 10.

$$F = (P_1 - P_0)\,A$$

$$F = PA\left(\frac{V_1}{V}\right)^{\gamma} - P_0 A$$

F_1 is the initial force;
V_1 is the initial volume at a pressure of P_1;
V is the volume and A the effective area at the pressure P.

The volumes and areas are obtained from the static curves.

In order to calculate the dynamic spring rate (where this value is not given in the published data), a first force at a height slightly above and a second force at a height slightly below the working height are calculated (a total height difference of 25 mm can be used); the spring rate is then calculated as the force difference divided by the height difference. Using this technique, the spring rate is given by a relationship of the form:

$$k = \left\{P\left[A_2\left(\frac{V}{V_2}\right)^{\gamma} - A_1\left(\frac{V}{V_1}\right)^{\gamma}\right] - P_0\,(A_2 - A_1)\right\}\frac{1}{L}$$

L is the height difference (25 mm, if that is the height difference chosen), and in this instance the suffixes 1 and 2 refer to values respectively above and below the working height.

The natural frequency can be calculated as before, using the calculated stiffness value.

The relationship between the forcing frequency and the natural frequency should be chosen to give the required degree of isolation, as determined from Figure 11.

General consideration in the use of air springs as isolators

It is recommended that, when using the air spring as a vibration isolator, the ratio of the forced frequency to the natural frequency should be about 3:1. This will give an isolation of about 90% (see Figure 11).

As the system is inherently soft, precautions must be taken to ensure stability. The ideal arrangement is to locate the springs in the same horizontal plane as the centre of gravity. Where this is not possible, the guideline to be used is: the narrowest distance between the mounting points should be at least twice the height of the centre of gravity above the plane of the springs.

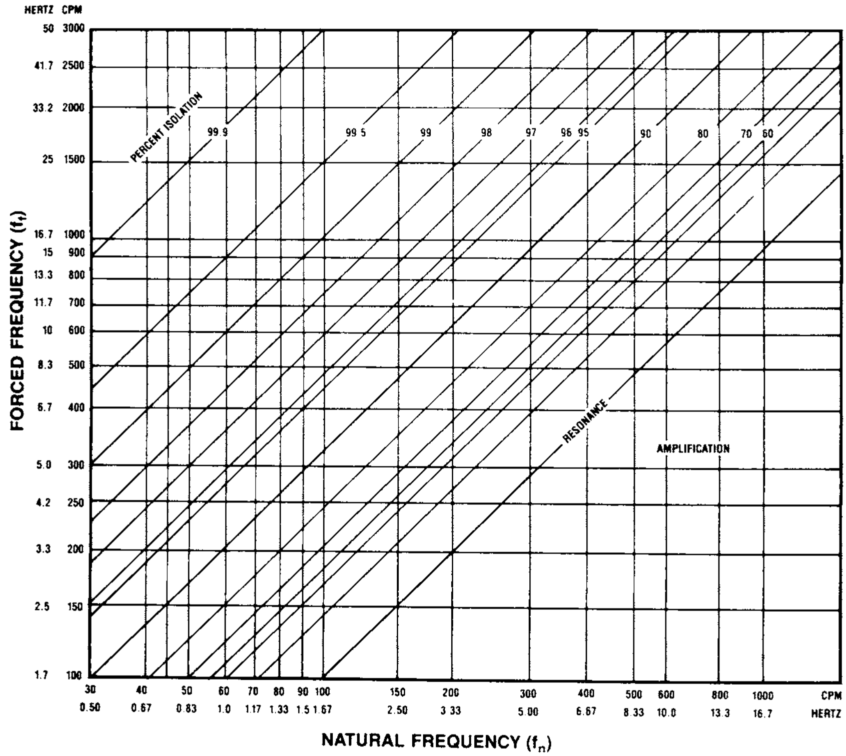


FIGURE 11 – Isolation chart. *(Firestone)*

The air spring should be used at the design height given in the published characteristics, because that height is the condition of maximum stability. Single and double convoluted springs can become unstable at a small distance away from the design height. The lateral stiffness (expressed in N/m) is of the order of 0.2 to 0.3 times the vertical stiffness. Rolling diaphragm types on the other hand can be designed to have a high lateral stiffness equal to or greater than the vertical stiffness.

The inherent damping in an air spring is about 0.03 times critical; this is so small that for most purposes it can be neglected. If damping is required, some external means has to be provided.

PNEUMATIC CONVEYING

Pneumatic conveyance in pipelines

Pneumatic conveying is the transport of bulk materials through a pipeline by air pressure or vacuum. Materials that can be handled range from asbestos with a bulk density of 100 kg/m^3 to crushed stone with a density of 1500 kg/m. The advantages of pneumatic conveying over mechanical conveying include safer working conditions (clean atmosphere and reduced fire hazards), greater flexibility, freedom from contamination and the ease in which a change of direction can be achieved.

It has to be admitted that the cost of air compression is likely to be higher than that of pure mechanical transport, particularly when the transported material requires a high degree of purity in the air. Fragile materials may not be suitable for pneumatic conveying, but most other materials and some manufactured components lend themselves to this form of transport.

The following types of pneumatic conveyors are available:

- Vacuum system, similar in principle to a domestic vacuum cleaner.
- Low pressure system, up to 1 bar.
- Medium pressure system, from 1 bar to 3 bar.
- High pressure system 3 bar to 8 bar.
- Pulse phase system.
- Combination vacuum/pressure systems.
- Air activated gravity conveyor.

The choice of a suitable system will depend primarily on the material to be transported – its density, particle size, moisture content and abrasiveness. There is a great deal of skill needed in choosing a suitable conveying method, so anyone contemplating installing a system would be well advised to approach a company with a wide experience in the various techniques. One can do no more here than indicate some of the factors that should be considered.

Vacuum systems

This uses a high velocity (up to 40 m/s) airstream to suspend the material in the pipe, using a vacuum up to 400 mbar.

The materials suitable for vacuum transport are dry, pulverised and crushed granular with a small particle size and a low density. Under ideal conditions, it is claimed that the conveying distance can be as much as 500 m, but in practice the maximum distance is likely to be rather less. Optimum design would require the internal pipe diameter to increase in steps along its length so as to stabilize the velocity. As in all systems, the limitation on conveying length is the pressure loss that occurs through pipeline friction. With a vacuum system the pressure loss can be no more than the vacuum depression, but with a pressure system, the loss through friction can always be compensated by increasing the positive pressure. The energy consumption will be between 1.5 and 5 kW hr per tonne of material, depending on the density and conveying distance. This makes it the most expensive method in power consumption, but the simplicity of installation and low capital cost makes it appropriate for many situations.

Vacuum systems are ideal where several pick-up points are required in one line. Another advantage is the ease with which material can be introduced into the pipeline. The simplest way is from an open container such as a ship's hold where the material is admitted with the air. In this case the material may have to be lifted through a considerable height and the system is then known as a pneumatic elevator.

When the material is in a hopper, there are several forms of feed device. One such is a rotary feeder which has a star wheel rotating in a close-fitting housing. For dry materials which flow easily, a simple on/off valve can be used and the material falls into the pipe by gravity. A positive low pressure may also be used to fluidize the hopper.

The suction is usually generated by a turbo blower (centrifugal or axial). The same equipment can be used for both suction and low pressure conveying systems.

Low pressure systems

The distinction between low, medium and high pressure systems is related more to the means adopted for producing the pressure than to their application to different materials. Some materials can be conveyed at all pressure regimes, but the main application of low pressure conveying is for dry, low density materials. Turbo blowers or Roots-type blowers are commonly used for pressures up to 1 bar. For pressures up to 0.3 bar a simple fan may be used. The velocity in the pipe is limited to 20 m/s, so this method is more appropriate for fragile materials than the vacuum method. The power used is between 0.5 and 3.0 kW hr per tonne, depending on density and distance.

Because of the positive pressure in the line, special methods have to be used to introduce the material into the pipeline against the positive internal pressure. Close fitting feed mechanisms are required for two reasons: that air should not be wasted through leakage; and when dusty or unpleasant materials are being handled, they are not blown out of the hopper into the atmosphere. The system is suitable where there is only a single pick-up point with the option of multiple discharge points.

When using a pressure below about 0.2 bar, it is possible to use a venturi-type pick up, provided that the material is suitable and is carefully metered; a venturi feed cannot handle plugs of material or deal with an excess of capacity that would inhibit the venturi effect. A rotary feeder is the customary form of injecting the material into the pipe, but care must be taken that the feed mechanism does not damage the material, Figure 1.

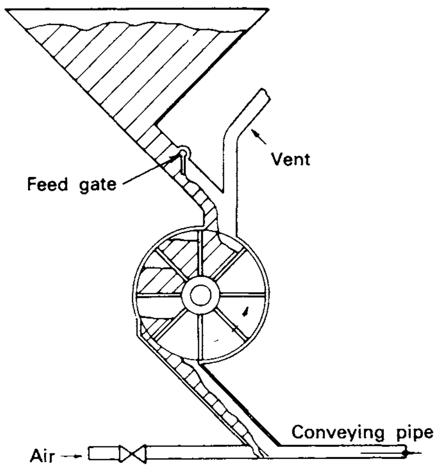


FIGURE 1 – Feed into air stream using a rotary lock to meter powder and act as a pressure seal.

Medium pressure systems

In this system, the material has to be forced into the line through a feed pump. It is most successful when dealing with materials which can be fluidised and then behave like viscous liquids (known as fluid solids); dry and fine powders are most suitable. The most successful pump for this purpose is a rotating screw, of which several makes are available.

The Mono pump is one type in which a specially shaped rotor gyrates in a casing and so causes pockets of fluidized powder to be drawn in at the intake and pumped into the pipeline. Another type is the Fuller-Kinyon pump, which is a rotating screw conveyor incorporating a non-return valve at the delivery, Figure 2. Any pump used for this purpose has to be chosen to resist the abrasive or corrosive action of the powder. The pump chosen has to operate against the pressure in the line and be well sealed to prevent leakage of the air back into the intake.

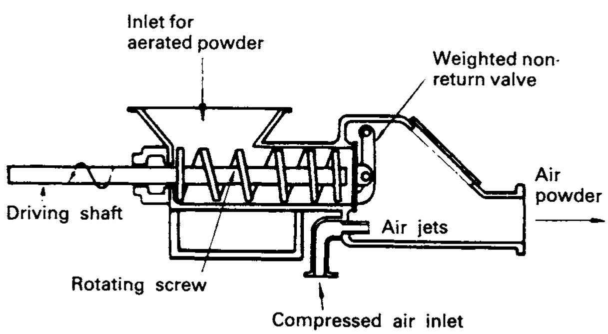


FIGURE 2 – Fuller-Kinyon pump.

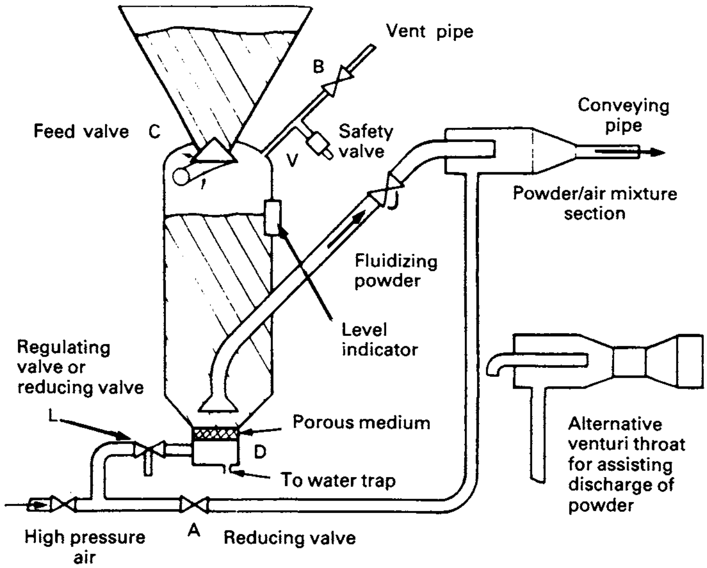


FIGURE 3 – Air pressure assisted gravity feed unit for powders needing fluidisation, batch operations.

High pressure systems

When the air pressure is high, the material is transported in a dense phase compared with medium and low pressure systems which use a dilute phase. Dense phase means that the fluidized material moves as a compact slug along the pipe. It is suitable both for powders that may be fluidized and for coarse and wet materials. It may also be used for a range of materials such as manufactured components and slaughterhouse residue. The material/air mass ratio is in excess of 50:1, so it is reasonably economical in the use of air. One method of introducing powdered material into the air is through a blow-tank, Figure 3. The tank has to be designed as a pressure vessel. The method is essentially a batch (non-continuous) method, although it is possible to use twin tanks and switch between the two, approximating to a continuous feed.

Pulse phase systems

This is a type of medium pressure (between 1 and 2 bar) system where the material is transported in discrete plugs. Material/air ratios in excess of 300:1 have been recorded; the air consumption is low and so this can be a very economical method. In Figure 4, air is injected into the vessel to fluidize the material; beyond the discharge valve at the base of the hopper is an air knife which injects pulses of air into the conveying line, and as a result the material is divided into plugs. When the full batch of material has been transported, the vessel is returned to atmospheric conditions, the inlet valve opens and the cycle repeats automatically.

Combination vacuum/pressure systems

This is a useful system when conveying from several pick-up points to several discharge

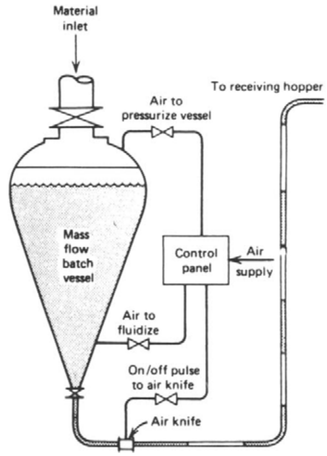


FIGURE 4 – Pulse phase concept. *(Sturtevant)*

points. The pick-up region is under vacuum and the delivery region is under pressure. The same blower can be used for both regions, but this places restrictions on the maximum positive pressure that can be generated, so it is more common to use both an exhauster and a blower and keep the two pressure regions separate.

Air-activated conveyor

This method (Figure 5) can be used when the material is to be transported over a distance with a vertical component. Air is used to fluidize the material which then moves along the incline under gravity. In normal conditions, a powder runs down an incline only when the angle of the incline is larger than the angle of repose. If the powder is fluidized, the natural angle of repose is reduced. As an example, a powder which has an angle of repose of 40° will require a chute set at an angle of 45°, but when fluidized the powder will flow down a chute of 2.5°. Even material which cannot be fluidized in the conventional sense may still benefit from a supply of air to the underside of a porous trough, which reduces the coefficient of friction.

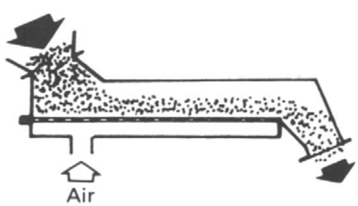


FIGURE 5

Separation methods

The material has to be separated from the air at the delivery point. Usually, a cyclone is needed for primary separation, with the outlet filtered. It is desirable to retain all the

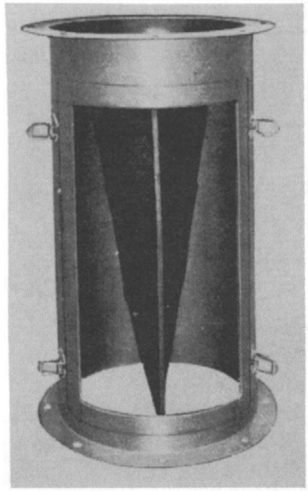


FIGURE 6 – Vacuum valve with access door removed. It consists of a steel funnel and a rubber sleeve. The sleeve is held in a collapsed condition by the vacuum on the conveying pipe. When the material in the hopper overcomes the vacuum, the valve opens. *(Sturtevant)*

material in the line and avoid unpleasant dust, so an efficient filter system has to be devised. For materials that do not cause problems if a small proportion escapes with the exhausting air, a fabric bag is satisfactory. The cyclone is connected to a hopper from which the material is taken by a rotary valve, this is similar to the method shown for introducing material into the pipe as illustrated in Figure 1. Another useful device which is suitable for vacuum lines is the vacuum valve, Figure 6.

Calculations on the power absorbed in pneumatic conveying

As indicated above, the design of conveying systems depends on practical experience. The conveying speed for various materials and the most suitable pressure regime cannot always be predicted without trials. However it may be helpful to indicate some of the theoretical concepts that can be used to analyse the power required. The treatment below is applicable to dilute phase systems (pressure or vacuum) only.

The pressure difference from one end of a pipeline to another is due to:

- Acceleration of the powder from rest
- Pipeline friction
- Changes of direction
- Gravitational forces.

The pressure difference required to accelerate the powder from rest is given by

$$\Delta P = \frac{F_1 V^2 \rho}{2}$$

where ΔP is the pressure difference, F_1 is the pick-up factor, V is the air velocity and ρ is the density of the powder/air mixture.

Usually, because the weight of the material being conveyed is so much greater than that of the air, the mixture density is accurately given by:

$$\rho = \frac{\text{Mass of material}}{\text{Volume of air at pipeline conditions}}$$

For some materials that are commonly conveyed, the value of the saturation is quoted; this is the reciprocal of the density. The pick-up factor varies with the feed design method, but it usually lies between 2 and 3; a value of 2.5 is customarily taken. The actual air velocity can be used, calculated from volumetric flow and pipe diameter. The ideal velocity for the common conveyed materials can often be obtained from published data.

Once the material has been picked up, it is conveyed along the pipe at constant velocity. The pressure drop caused by pipeline friction is calculated in a similar way to that of turbulent flow of a homogenous fluid.

$$\Delta P = \frac{F_2 L V^2 \rho}{2D}$$

F_2 is the conveying factor, L the pipeline length, D the internal diameter.

F_2 depends on a large number of factors – the size, shape and density of the particles, but primarily on the velocity of the flow. Figure 7 may be used if test results are unknown, with a generous factor of about 50% to account for uncertainty.

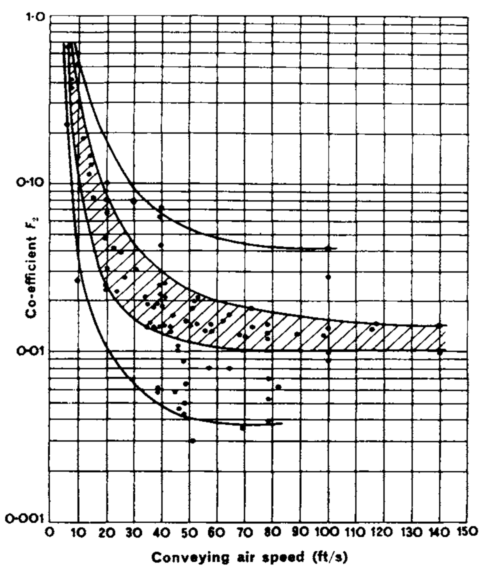


FIGURE 7 – Values of the coefficient F_2 plotted against speed of the conveying air for a large number of controlled tests. Note the abscissa is in ft/s.

Changes in direction result in a pressure loss (for a single right angle bend) of

$$\Delta P = \frac{F_3 V^2 \rho}{2}$$

The value of F_3 is higher than the usual one for gas flow.

TABLE 1 – Recommended values for F_3.

Ratio of bend radius/pipe diameter	F_3
2	1.5
4	0.75
6 or more	0.5

Pressure loss due to gravitation is applicable to pipelines which have to be elevated during transport. If the pipeline has a net fall this will help the conveyance, and the pressure loss becomes a pressure gain. The formula for pressure loss is given by

$$\Delta P = Hg\rho$$

where g is the gravitational constant and H is the height.

The total pressure loss comes from the four sources given above.

$$\Delta P = \rho \frac{V^2}{2} \left\{ (F_1 + LF_2/D\, F_3) + Hg \right\}$$

The total power required for conveying is then

$$W = \Delta P \frac{\pi D^2}{4} V$$

Note that the above equations are correct with consistent units. In particular with L, D and H in metres, V in m/s, P in N/m^2, W is in watts. If P is required in bar, the correct conversion factor must be used.

There will be additional power required for feeding material into and extracting it from the pipeline, to overcome leakage and pressure drop through the separation cyclones at the end of the conveyance.

Air lift pumps

This is a method of pumping water from the bottom of a well by injecting air at the base of the pumping tube. The air mixes with the water and produces a mixture which has a lower mean density than the water alone, so the static head of the water can be used to force the mixture to a considerable height. This system is less efficient than other forms of deep-well pumps; usually the compressor power required will be about 2 to 3 times that of a shaft driven pump. It is however useful for temporary installations and where it has to deal with a mixture of sand, grit or coarse mud. In this latter role it is commonly used for silt removal around submerged wrecks or for dredging. The size of solid objects that can be handled can exceed half the diameter of the pipe.

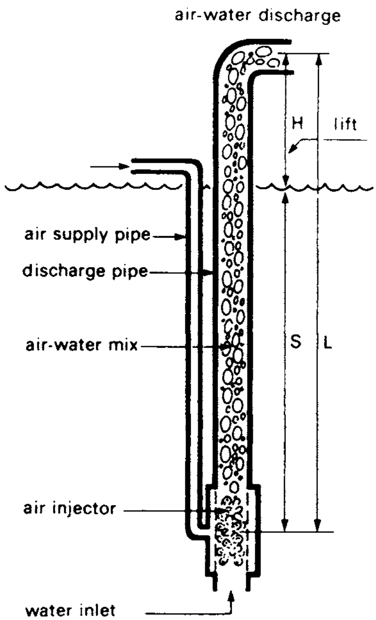


FIGURE 8 – Air lift pump.
(Atlas Copco)

In Figure 8, the distance H is known as the pumping lift and S is the submergence.

$$L = H + S$$

The percentage submergence is defined as

$$S\% = 100\ S/L$$

For low lifts (to about 10 m), a percentage submergence of 80% is possible, but for higher lifts (up to about 30 m), a percentage submergence of 30% is the limit. In order to assess the quantity of air required, an empirical formula, developed from a number of tests can be used:

$$q = \frac{H}{C \log_{10} [(S + 10) / 10]}$$

q is the ratio of (volume of free air)/(volume of water) and heights are in metres.
C is an empirical constant given in Table 2

TABLE 2 – Values of constant C

Lift H (m)	*Constant C*
10 to 20	390
20 to 60	370
60 to 150	342
150 to 200	290
200 to 250	247

Although extremes of percentage submergence as mentioned above can be employed, the following recommendations will ensure good efficiency.

TABLE 3 – Recommended submergence

Lift H (m)	*Ratio of submergence/lift*
15	2.5
23	2.0
30	1.6
45	1.5
60	1.3
80	1.2
100 +	1.0

The size of the rising pipe must be chosen correctly. The velocity should not be so great that there is too large a friction loss and not so small that the air rises through the water rather than lifting it. At the point of injection the velocity should be between 2 and 4 m/s and at discharge between 4 m/s and 14 m/s. The velocity is calculated from the combined volume of the air and water and the cross-sectional area of the pipe, the volume changing with pressure. For large lifts, in order to keep the velocity between the above limits, it may be necessary to increase the pipe diameters in steps towards the surface. The air pressure must be selected so that it is larger than the local static water pressure at the point of injection.

Figure 8 shows the most common arrangement of air-lift pumping with the air supply pipe external to the discharge pipe. This is the most efficient system, but it takes up more room in the well than the alternative arrangement where the air pipe is enclosed within the discharge pipe. The latter can accommodate a larger diameter of pipe up to the bore of the well and so can handle more water for a given well size; if there are variations in water level, adjustments for efficient operation can be easily made by altering the length of the air line.

Compressed air for blending and mixing

Powders which can be fluidized, can usually be mixed in the fluidized state more efficiently than by mechanical means; one example is the blending of sand ground to different size gradings. Blending by air produces a more uniform mixture than by mechanical blending.

There are practical limitations when attempting to blend powders with different densities and particle sizes. One manufacturer claims that mixing can be achieved with a density ratio of 5:1 and a size range of 10:1. Powders can be mixed:

- By feeding them in the required proportions into the same conveying pipeline.
- In a silo with aeration pads in the base.
- In a silo with air-jet mixers.

Mixing of powders and liquids can be achieved by spraying the liquid in a fine mist over a fluidized bed.

The volume of air required depends on density, particle size and rate of mixing required. It is best determined by experiment.

Compressed air can also be used for mixing liquids and slurries. This can be simply done by admitting air through a perforated pipe in the base of the mixing tank. For this application, recommended air flows are available, depending on the submergence of the pipe below the surface and the cross-sectional area of the tank. Table 4 can be used for an initial estimate of the air flow required.

The values of air flow are for moderate agitation. For complete agitation multiply the table values by 2 and for violent agitation multiply by 4. The holes admitting the air should be evenly distributed over the base of the tank. The total orifice area can be calculated from the nozzle equations given in the chapter on Pipe Flow. The back pressure on the nozzle will be that of the head of water.

TABLE 4 – Mixing liquids and slurries

Submergence (m)	*m^3 of free air per m^2 of liquid*
0.5	0.59
1.0	0.37
2.0	0.24
3.0	0.19
4.0	0.16
5.0	0.141
6.0	0.125

COMPRESSED AIR IN MARINE APPLICATIONS

There are several ways in which compressed air finds an application offshore: the supply of breathing air for divers, for engine starting, for operation of air tools on board ship and underwater, air lift dredging and for seismic surveys. Engine starting and air lift dredging are dealt with separately in other chapters.

Breathing air is covered in outline in that chapter. For underwater air supply, the pressure requirement may be up to 400 bar and special marine sets are available to supply pressurised and treated air at high pressure, see for example Figure 1.

General use of compressed air for marine work

Many of the tools that have been described in the chapters on contractors and industrial tools are suitable for general marine work. Shipboard compressors, both stationary and portable, are supplied by most compressor manufacturers; there may be special regulations which have to be satisfied, *e.g.* Lloyds or U.S. Coastguard. Stationary compressors using sea water for cooling are supplied by some manufacturers.

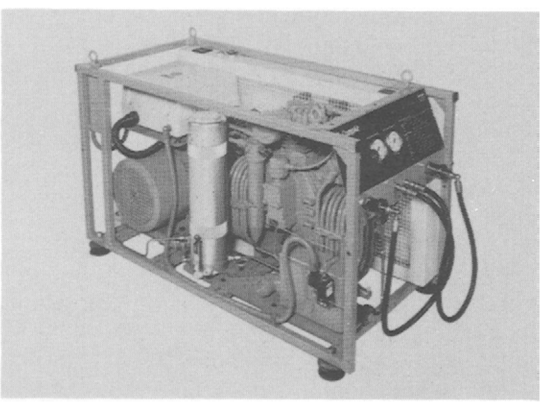


FIGURE 1 – Breathing air centre for shipboard use. 400 bar pressure p to 865 l/min. Available in electric, petrol or diesel drives. *(CompAir Reavell)*

Corrosion in the presence of salt-laden air is a problem which should always be borne in mind. Provided that the suppliers are made aware of the use to which their equipment is to be put and any special precautions, particularly in respect of lubrication and maintenance schedules, are strictly followed, there is no reason why most pneumatic equipment should not prove as satisfactory at sea as on land. Tools which are used close to the water line for work on descaling and removal of marine growth are likely to be frequently immersed in water and may require special cleaning after each shift. A useful technique consists in immersing the tool in paraffin or diesel oil to wash out the seawater and then thorough lubrication with oil; for short periods, the tool can be left immersed in the paraffin.

There are some compressed air applications which are of particular interest in offshore applications.

Prospecting with compressed air

Oceanographic research undertaken to improve our knowledge of the Earth's structure can make use of compressed air. Figure 2 shows how high pressure air (up to 350 bar) is fired in pulses from special guns at the area being surveyed. The air pulses create shock waves which echo from the survey area, either land mass or sub-strata. The echos are picked up by sensitive electronic devices to provide data on the structure and content of the survey area.

Drill string compensator system

This is a motion compensating system developed to nullify the effects of the heave of the drilling platform or vessel on the drill string or hook supported equipment. The compen-

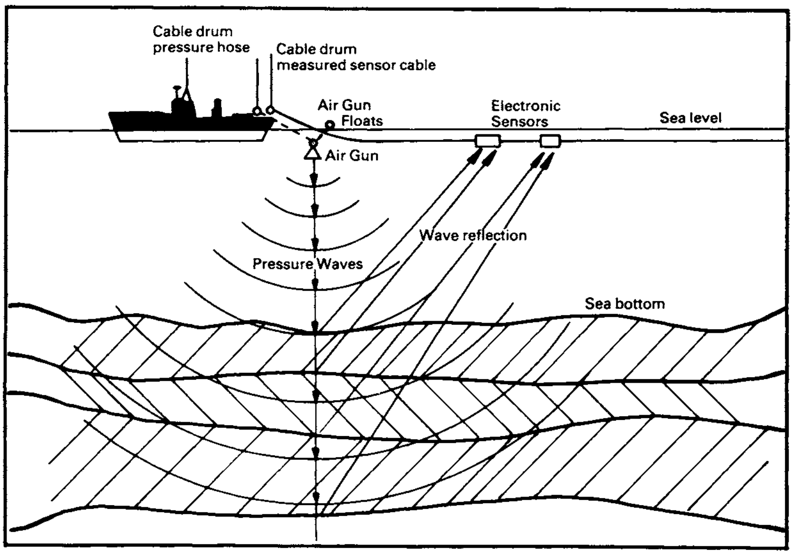


FIGURE 2 – Sketch showing principle used for firing compressed air in marine seismic survey applications.

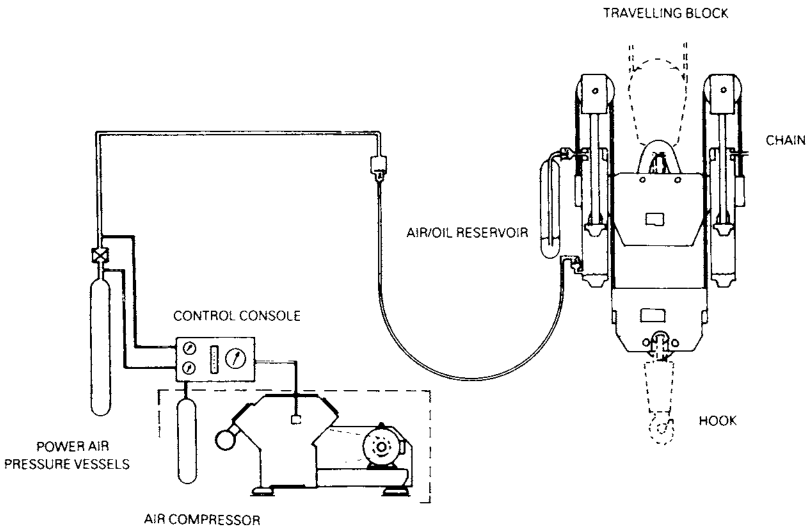


FIGURE 3 – Drill string compensator for offshore oil rigs.

sator shown in Figure 3 comprises two compression-loaded hydraulic-pneumatic cylinders. The cylinders are supplied with high pressure air which, in the application illustrated, is 163 bar. As the rig heaves upwards, the compensator cylinders retract and the hook moves downwards to maintain the selected drilling load. Thus while the drill platform and compensator move, the hook remains fixed relative to the Earth. Use of these compensators ensures that drilling can proceed in high heave conditions.

Use of pneumatic tools underwater

In modest depths of water, down to about 10 m, the standard air tool can be used without any difficulty apart from the worsened visibility caused by the exhausting air. The back pressure caused by the head of water acting on the exhaust port causes a progressive drop in performance; this is particularly true of percussive tools, which become completely ineffective at a depth of 30 m. From tests performed on a medium size percussive drill, operating at 6 bar, Table 1 has been prepared.

TABLE 1 – Performance of rock drill under back pressure

Depth (m)	*Gauge pressure (bar)*	*Performance ratio (1)*	*Performance ratio (2)*
0	0	1.0	1.0
7.5	0.8	0.59	0.75
15	1.5	0.22	0.44
30	3.1	0.0	0.20
60	6.2	–	0.0

Note: The performance ratio is the proportion of the output energy of the tool available at depth.

Condition (1) is for a constant 6 bar at the inlet; condition (2) is for a constant 6 bar pressure drop across the drill, achieved by increasing the inlet pressure.

It can be seen that it is possible to restore some of the lost performance by increasing the inlet pressure but only to a limited extent. It would be possible to design tools to work against a back pressure (a similar problem is faced when designing tools to work on a closed circuit system as discussed in an earlier chapter), but these are likely to remain theoretical concepts for the present.

In practice the best way of using tools at depth is to provide an exhaust boss which permits the connection of a hose to take the exhaust air back to the surface where it can be held bouyant at its open end by floats. Some manufacturers provide tools in this form, but often only to special order. Figure 4 shows one such modified tool. An exhaust hose gives the added advantage of improving visibility, but not all the air escapes through the exhaust port – there is plenty of leakage around the shank of the tool bit and from other unsealed joints, so ideally extra sealing is required for these regions. The exhaust hose must be generously sized, otherwise it would cause its own back pressure. Two further points are to be noted when using a return hose. Firstly, the inlet pressure must be higher than the local water pressure otherwise the water would leak into the tool. Secondly the return hose must be sufficiently robust so as not to collapse under external water pressure; conventional pneumatic hose has been found to be unsatisfactory in this application – either a wire wound hose (which is heavy and hard to manoeuvre) or a moulded PVC hose should be satisfactory.

Most modern tools as described in earlier chapters incorporate a noise muffler to meet onshore noise regulations, which is their main duty. To find a tool of the more traditional form with an exhaust port, which lends itself to the attachment of an exhaust hose, may

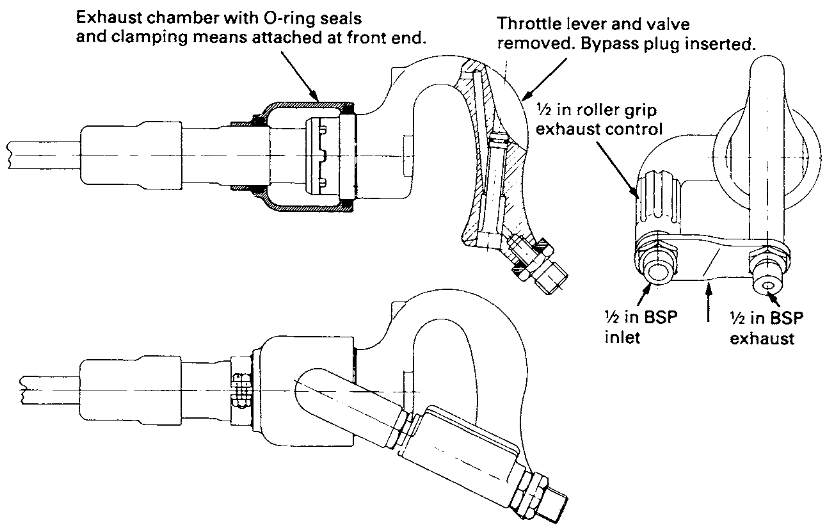


FIGURE 4 – Chipping hammer adapted for underwater use. Note the exhaust chamber seal and control on the exhaust. *(CompAir Holman)*

not be easy. A special tool may need to be designed and made. The general principles illustrated in Figure 4 should be followed.

An effective way of keeping a tool free from water, when not being used, is to transfer the on/off control from the inlet stem to the exhaust port; the tool is then kept continually under pressure and water is unable to get access to the working parts.

When drilling rock or concrete, high pressure water flushing has proved to be more efficient than air flushing. All tools require a hold-down force to keep them applied to the work; this may be difficult under water, so some means of reaction must be available to the operator, probably by anchoring him to the work surface.

AIR FILMS

The use of an air cushion to reduce friction is well known in various applications – air bearings, the floating of one machine surface over another and moving heavy loads. A similar analytical approach can be adopted for all these applications.

A thrust bearing can adopt one of the forms shown in Figure 1 – a central recess or an annular bearing.

The load that such a bearing can support is given by

$$F = C_L\, A\, P$$

F is the load carried, C_L is the load coefficient, A is the total pad area ($= \pi r_0^2$) and P the supply pressure (gauge). The value of C_L can be estimated from Figure 2. It can be seen that for bearings with small pockets, a value of $C = 0.25$ is a reasonable approximation and this value is often taken as an initial estimate. The basic principle to be used for calculating the feed orifice diameter is that it should be smaller than the circumferential leakage area, *i.e.* the orifice area must be greater than $2\pi r_0 h$. This should ensure that the suspension system is stable, although if maximum stability is required, unpocketed orifices are preferred.

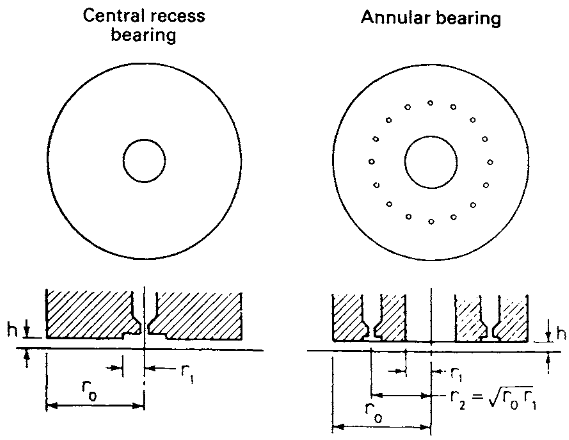


FIGURE 1 – Types of thrust bearings.

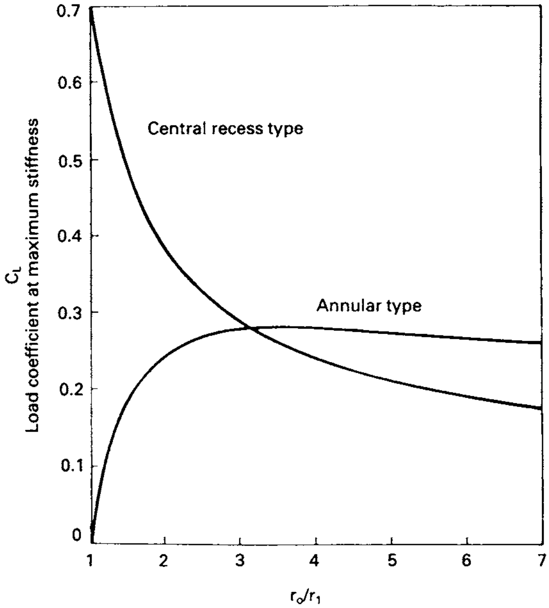


FIGURE 2

Design should aim at maximum stiffness (K = load/vertical deflection).
For pocketed orifices, K = 1.42 F/h
For unpocketed orifices, K = 0.95 F/h

The value of h is very small when smooth machined surfaces are employed (typically 0.025 mm). When the application is for moving loads over rough surfaces, care should be taken that h is greater than the roughness.

Bearings for use on precision surfaces

An important application of air bearings is their use for moving heavy components over surface plates and machine-tool surfaces. Precision surfaces are expensive to produce and subject to wear in use, resulting in progressive deterioration. Air bearings can be used to overcome this problem and also to allow for ease of manipulation.

In these bearings, the air thickness is about 0.025 mm with a surface pressure of 1 to 2 bar. The air flow requirements are modest, but the air quality should be good; dry filtered air is necessary so that there is no chance either of corrosion or dirt affecting the surface. The air supply for commercially available bearings is taken from shop air. Table 1 gives typical data.

It is not necessary that the surface over which the bearing moves shall be continuous. If the surface has slots or holes, the bearing will work with a reduced capacity approximately proportional to the area that remains unvented.

The same principle of using air bearings is adopted in more permanent installations on rotary tables used for paint spraying, welding fixtures and for work transfer tables.

TABLE 1 – Capacity of flat air bearings

Load (kg)	*Dimensions (mm)*	*Airflow m^3/min*
450	150 x 150 (or 150 dia)	0.085
900	150 x 300	0.17
675	200 x 150	0.127
800	200 dia	0.15
1000	200 x 300	0.255
1350	300 x 300 (or 300 dia)	0.34
1600	300 x 450	0.51
1500	400 dia	0.45
2000	450 x 450	0.85
1800	500 dia	0.75
2700	600 x 600	1.36

Figure 3 shows a vehicle turntable. The low friction allows for rotation by hand or if required a power drive can be supplied. The air consumption is low and so for fixed installations these tables are preferable to the air skates described below.

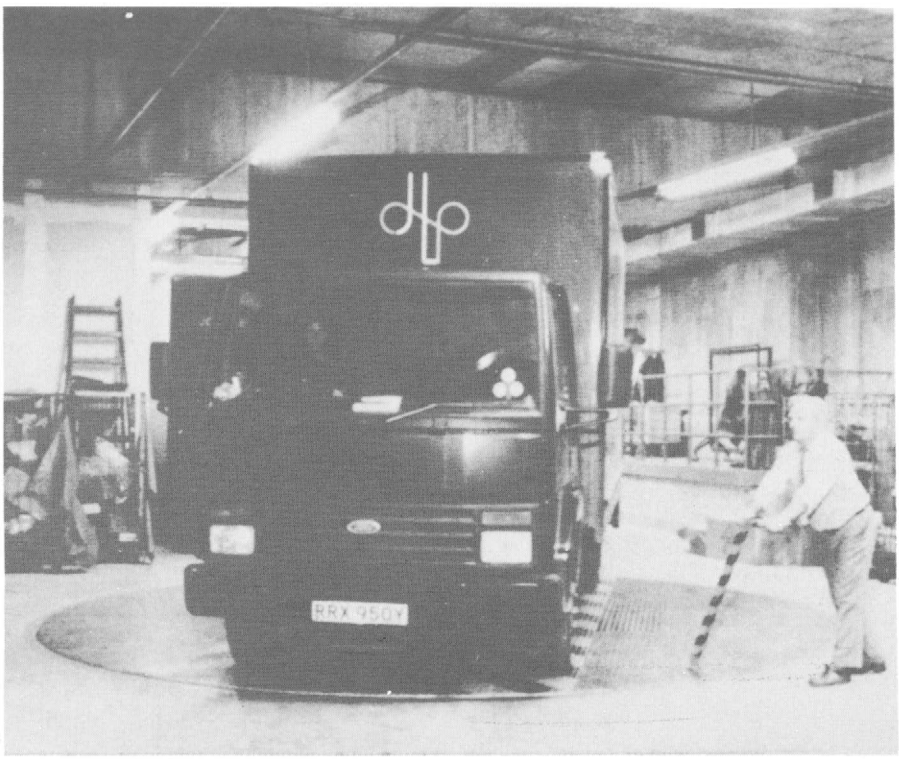


FIGURE 3 – Air film vehicle turntable. The turntable sits in a shallow pit, 150 mm deep, allowing up to 20 tonnes to be rotated by hand. *(Hovair Systems)*

Air skates

These are suitable for moving machine tools and other heavy loads over a concrete or other level floor. The method of operation is shown in Figure 4, and a set of four bearings supplied ready for installation in Figure 5. Three or more of these skates are required for stability under load. The air pressure (usually shop air at 5 to 6 bar) inflates the urethane diaphragm creating a pressure zone which lifts the load until controlled air leakage forms a thin film between diaphragm and floor. Once floating on its air film, the load is virtually frictionless and may be moved in any direction with a minimum of effort. The ground pressure, which varies with the quality of the operating surfaces, is from 1 to 4 bar. The air consumption also depends on the quality of the surface as in Figure 6. It is really only practical to use these skates over a reasonably smooth surface. As can be seen from the

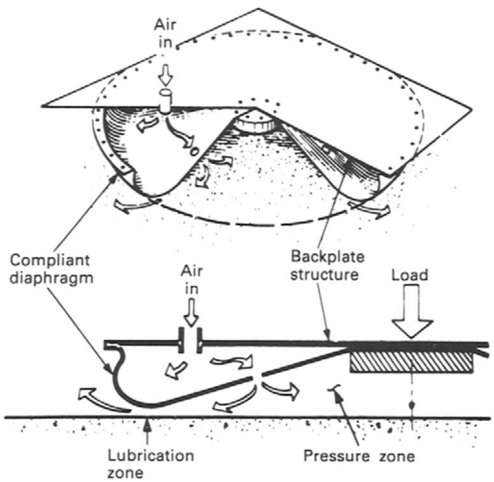


FIGURE 4 – Function of air skates.

TABLE 2 – Capacity of air skates

Load per skate (kg)		*Dimensions (mm)*	*Bearing rise (mm)*
Std duty	*Heavy duty*	*Length x width x height*	
500	1000	320 x 320 x 51	8 – 14
1000	2000	425 x 425 x 51	10 – 16
2000	4000	610 x 629 x 51	12 – 20
3000	6000	762 x 768 x 57	12 – 20
5000	10 000	914 x 914 x 57	11 – 19
7000	14 000	1067 x 1067 x 57	11 – 21
9000	18 000	1168 x 1168 x 57	15 – 27
15 000	30 000	1778 x 1232 x 57	12 – 27

Note that the standard duty rating operates at 1 bar ground pressure and the heavy duty at 2 bar pressure.

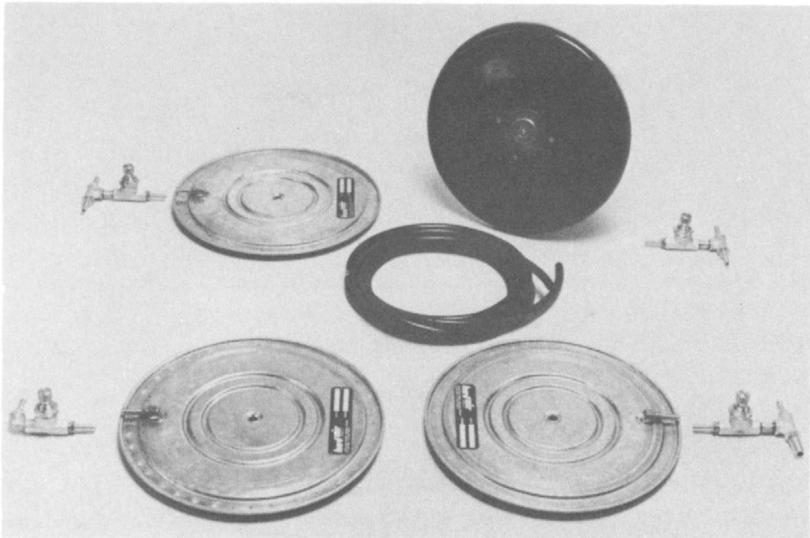


FIGURE 5 – Air bearing installation. Available from 255 mm diameter to 355 mm diameters and capacities from 250 kg to 600 kg. *(Hovair Systems)*

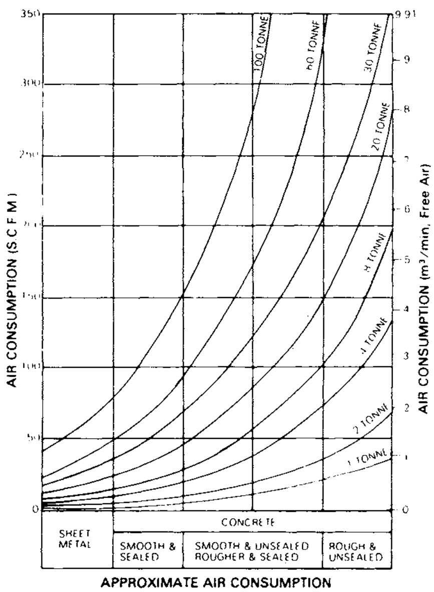


FIGURE 6 – Approximate air consumption of air skates. *(Hovair Systems)*

figure, the air consumption rises rapidly with increasing roughness; a temporary smooth surface such as a steel sheet may have to be laid where the surface is very rough.

To give some idea of the size and lift of a typical skate, Table 2 gives typical information.

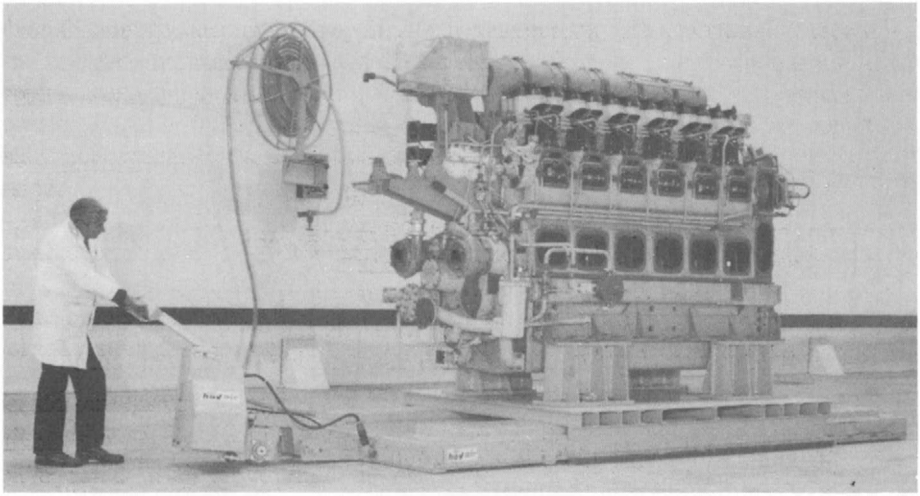


FIGURE 7 – Engine supported on an air platform manoeuvred by one man using an air trigger. *(Hovair Systems)*

Figure 7 shows how a 40 tonne engine, supported on an air film platform can be moved by an air operated tugger.

Journal and thrust bearings

These are of two types: self-acting and externally pressurised.

Self-acting bearings are similar in principle to liquid hydrodynamic bearings. They are used in the form of smooth surface cylindrical journals and flat thrust bearings. The main drawback of air bearings in this form is that they lack the boundary lubrication property of liquid lubricants so they have high friction at start and stop, limiting their use to about 0.5 bar over the projected bearing area. This is a subject where expert knowledge is required for design.

Externally pressurised bearings are used in high speed (of the order of 25 000 rev/min),

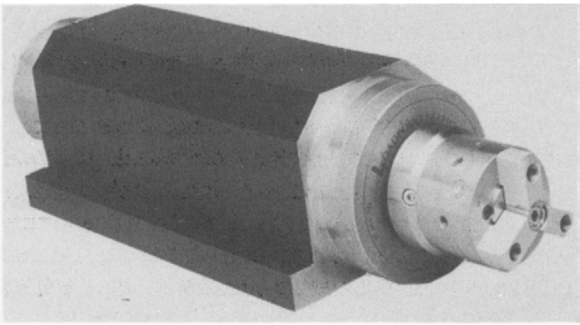


FIGURE 8 – Air bearing for diamond machining incorporating an air operated chuck. *(Loadpoint)*

low friction applications for such purposes as diamond machining and dicing (precision machining of semiconductor materials) as illustrated in Figure 8. Factors influencing the design are: pocketed or non-pocketed feed holes, bearing stiffness to achieve the desired resonant frequency, available pressure. For very high speed applications, water cooling is incorporated in the bearings. Charts are available for detailed design purposes, see for example Tribology Handbook published by Butterworth.

AIR BUBBLE TECHNIQUES

Air bubble techniques are based on the bubble barrier produced when compressed air is fed into a submerged, perforated hose, creating a series of bubble plumes rising from the holes. The rising bubbles cause a vertical current of air and water to flow to the surface, in turn generating a flow of water towards the barrier in the lower layer of water and away from the barrier in the upper layer. This has a mixing function, which can be useful in aerating a stagnant lake.

Table 1 describes and illustrates various techniques developed by a major manufacturing company.

TABLE 1 – Air bubble techniques *(Atlas Copco)*

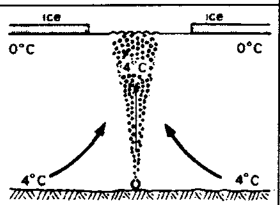
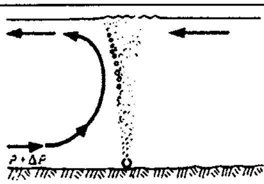
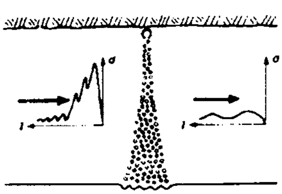
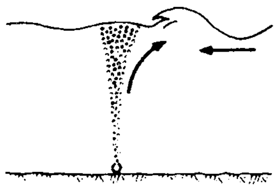
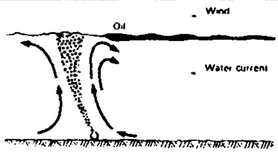
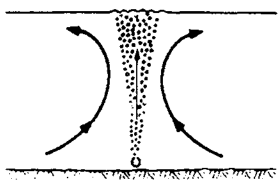
Application	*Diagrammatic*	*Description*
Ice-prevention		The bubble barrier in this case transports warmer bottom water to the surface, creating an ice-free area along the barrier. It has been used successfully to prevent ice damage in yacht marinas.
Reduction of salt intrusion		Here the bubble barrier stops and reverses the intrusion of salt water into flowing fresh water, much of which is then carried back out to see by the fresh water stream. This scheme is used in several Dutch locks.
Underwater blasting		The bubble barrier can considerably reduce the effect of shock waves when underwater blasting by reducing the maximum amplitude of the shock wave, *ie* subduing peak pressures. It cannot, however, reduce the total energy of the shock wave.

TABLE 1 – Air bubble techniques (continued) *(Atlas Copco)*

Application	*Diagrammatic*	*Description*
Pneumatic breakwater		Provided the generated surface velocity produced by the bubble barrier is high enough – *ie* exceeds 25% of the propagation velocity of the waves – then steep waves will break or be reduced in height. High airflow rates are required. This system has been used in Japan.
Oil-protection barriers		A bubble barrier can prevent the spread of oil slick from an oil spill by the surface velocity generated by the barrier. This system has been shown to work well in practice, but is still subject to further development.
Lake restoration		Basically, in this case, an air bubble generator is used to treat polluted lakes by aeration; also to promote water circulation in deep lakes. Primarily it can offer a solution where the main problem is oxygen deficiency.

AIR GAUGING

One important application of compressed air is in air gauging. Although recent developments in electronic gauging have in some applications superseded the use of air systems, there are situations in which it retains many advantages. It is a non- contact system, is self-centring and self-cleaning. It is now possible, with the use of an air-to-electronic transducer, to combine the benefits of the two systems.

Commercially available equipment is, in the main, confined to bore gauging and in this application it is a very quick and simple technique, capable of identifying taper, ovality and straightness of a bore.

Principles of operation

If the tube A which terminates in the jet J (Figure 1) is connected to a source of compressed air held at constant pressure, air will flow through the jet to atmosphere at a constant rate. If now the surface S is moved towards the jet, the escape of air will be impeded and the flow will begin to decrease. Continued advancement of the surface will steadily reduce the flow until finally with the surface in contact with the jet, the flow ceases. This simple device is a displacement-flow transducer which permits detection of the movement of the surface by observing the change in air flow.

In Figure 2, a regulator R maintains the incoming air at a constant pressure and a variable

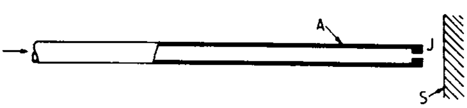


FIGURE 1

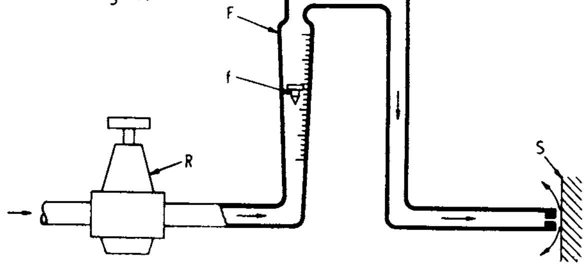


FIGURE 2

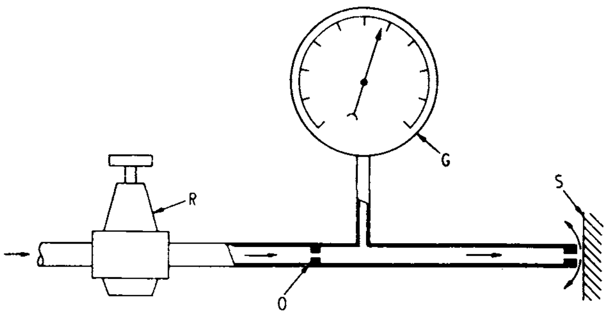


FIGURE 3

area flow meter F measures the flow of air through the jet. The flow responds to the change in flow, rising as the flow increases and falling as it decreases. The flowmeter can be graduated in units of length to give a scale which can be used to measure the displacement of the surface S.

It is not, however, essential to measure directly the changes in air flow; these changes can be converted into changes in air pressure by the method shown in Figure 3. A restriction O, called the control orifice, is introduced between the regulator and the jet, and the air pressure between this restriction and the jet is measured by means of a suitable pressure indicator G. This indicator, shown in Figure 3 in simple diagrammatic form as a pressure gauge, will register a lower pressure when the air flow through the jet increases and a higher pressure when it decreases. As before the scale of the instrument can be graduated in units of length and used for gauging. This arrangement is a displacement-pressure transducer. Most commercially available systems are of this type.

These are the basic ideas of air gauging and are simple in concept. What is important is that they can be used to build robust measuring instruments of extremely high accuracy and stability for use in precision engineering. Their magnification, *i.e.* the ratio of the movement of the indicator (the float in Figure 2 or the pointer in Figure 3) to the movement of the surface which produces it, varies from relatively low (1000) to very high (100 000). Magnifications of 10 000 or 20 000 are common and permit accurate inspection of close tolerance components. The true size of the components are obtained and errors of form can be investigated. The air gauging system thus offers advantages over inspection by limit gauging and can, when required, be used for selective assembly of mating components such as glandless spool valves. The gauging jet can be separated from the indicator (flowmeter or pressure indicator) by a suitable hose connection, so that remote reading can be arranged.

The open jet never makes contact with the work being gauged and may be described as a non-contact gauging element; it is suitable for many applications of air gauging. For others, *eg* when measuring components which have a rough surface finish or porous surfaces, it is better to use a contact gauging element, comprising a stylus, obturator and jet. This may take several forms, but the principle is shown in Figure 4 where it will be seen how the movement of the stylus, which is in contact with the work being gauged, changes

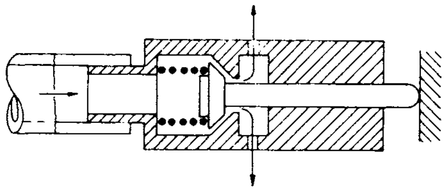


FIGURE 4

the flow of air through the jet. As in the case of the open jet, the changes of flow can be measured directly by a flowmeter or pressure indicator.

An air gauging system comprises an air gauge unit and a measuring head. The air gauge unit contains both the means to display the measured sizes (or to generate signals based on them), certain other items depending on type; when the variable measured is pressure it will contain the control orifice. The measuring head may contain a single gauging element, either contact or non-contact or two or more such elements. The form of the head and the number of gauging elements used will depend on the type of measurement to be made: length or thickness, internal diameter, external diameter, straightness, squareness *etc.*

The air supply for the gauging system will usually be drawn from the factory air line, but a local compressor may be employed.

The air gauge must be operated at constant pressure, which requires a pressure regulator, usually incorporated in the air gauge unit. It is essential that the supply pressure is significantly larger than the operating pressure. Systems using flow measurement normally operate at 0.7 bar, whereas systems using pressure measurement are normally from 3 to 7 bar. The air supplied to the unit must be clean and dry and free from oil vapour. The air consumption of a single unit is small (typically about 1 m^3/hour).

The air gauging principle shown in Figures 2 and 3 provides a means for comparing the sizes of like objects, *ie* it acts as a comparator. As with all comparators it requires standardisation before it can give a true size. Suitable setting standards are therefore required for use with the instrument and are employed in conjunction with simple controls for datum setting and fixing the magnification. In some cases, it is convenient to fix the magnification by using master jets which are substituted for the measuring head.

However precise the instrument used in measuring, it cannot give the correct answer if a poor inspection technique is employed. Change of temperature alters the size of the components being measured; difference of form between the standard and the component or errors in form in the component, may lead to false results.

Typical examples of air gauging

Some of the more direct applications of air gauging are illustrated in Figures 5 and 6, in which the gauging element is represented by an arrow. Figure 5 illustrates a single jet, and Figure 6 multiple jet systems.

One of the features of this system is its flexibility and in consequence its wide field of operation. It is particularly valuable for the simultaneous inspection of several dimen-

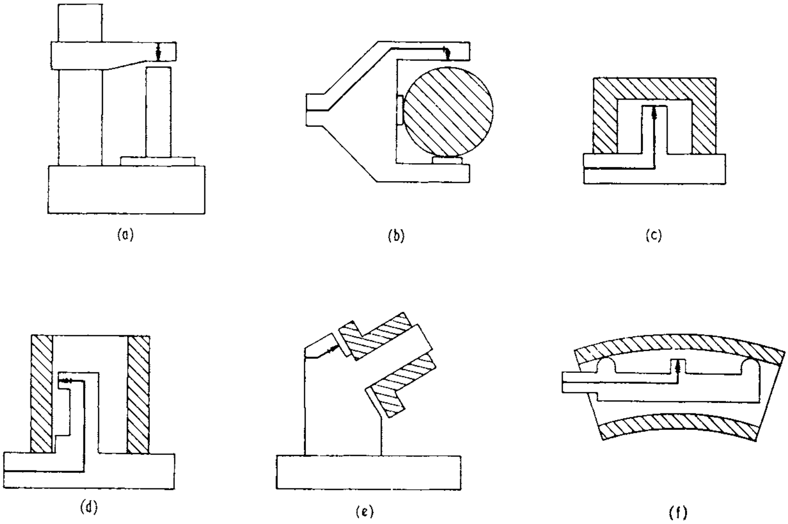


FIGURE 5

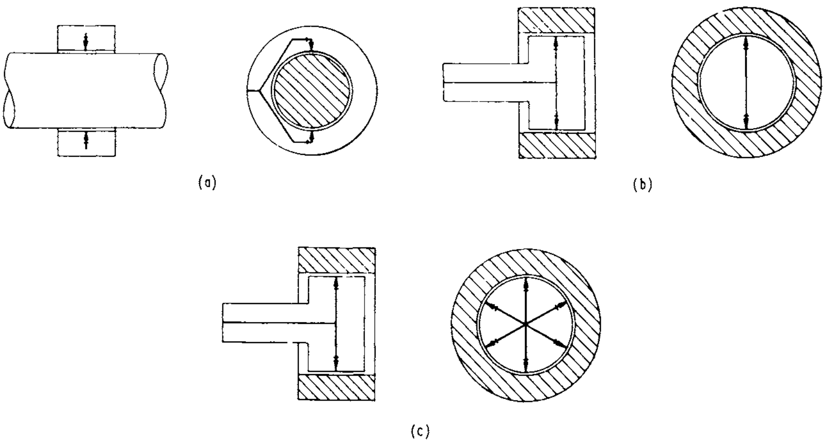


FIGURE 6

sions, and it can conveniently be employed on a machine tool to give measurement during production. Signal retainers and signal inverters can be incorporated; measurements can be converted into electrical signals for automatic control.

Circuit layouts are shown in Figures 7 and 8. Note that the system of Figure 8 incorporates means for regulating the pressure and setting the zero.

A wide range of air plugs are commercially available to measure tapers, ovality, multi-diameters, straightness and squareness.

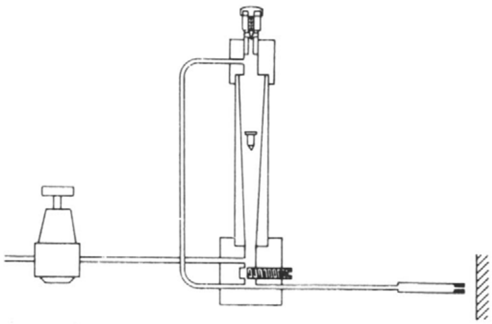


FIGURE 7 – System using flow indicator.

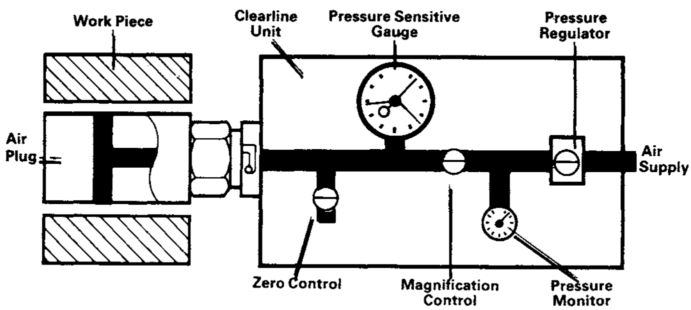


FIGURE 8 – System using a pressure gauge. *(Mercer Brown & Sharpe)*

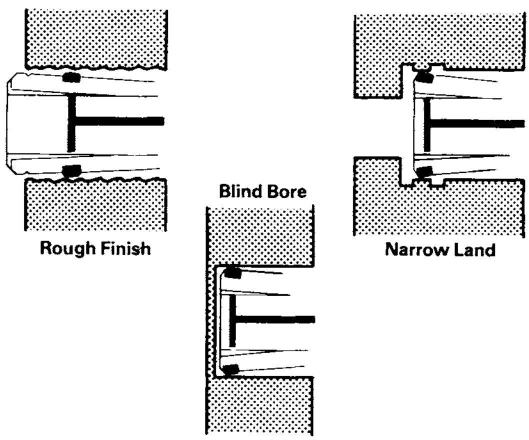


FIGURE 9 – Mechanical contact air gauging. The air plug has tungsten carbide pads mounted on reed springs. *(Mercer Brown & Sharpe)*

For mechanical contact air gauging, the air plug of Figure 9 can be used. This has pads which contact the measured surface and allows the air to pass through the gap made by the displaced pad.

Air/electronic gauging

The advantages of air gauging can be combined with an electronic display or for further control purposes. An air/electronic transducer can be incorporated in the system as shown in Figures 10 and 11. The transducer consists of a diaphragm which is sensitive to variations of pressure, whose movement is measured by an electronic probe. The signal can then read by an appropriate display unit, Figure 12.

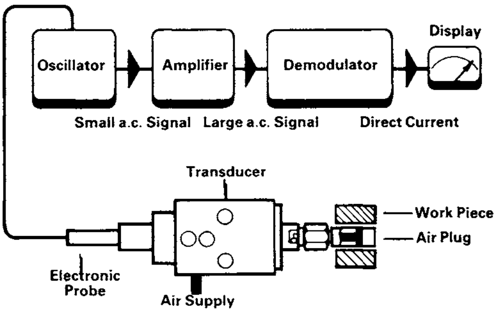


FIGURE 10 – Air/electronic gauging system. *(Mercer Brown & Sharpe)*

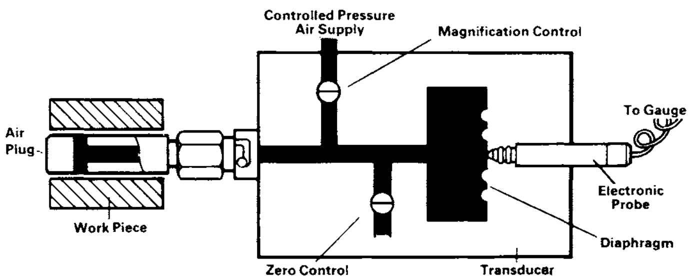


FIGURE 11 – Air/electronic transducer. *(Mercer Brown & Sharpe)*

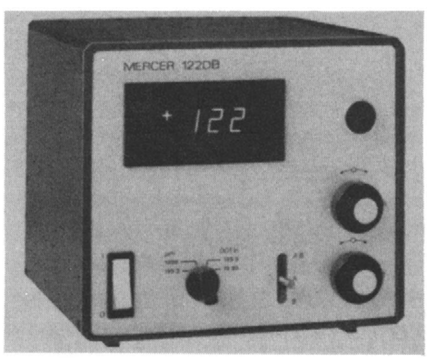


FIGURE 12 – Digital display unit.