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# Flow Control of Centrifugal Jet-Flap Blowers for Air-Cushion Vehicles

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**Air-cushion vehicles and surface-effect ships may require some form of dynamic lifting air control. An experimental investigation was carried out to demonstrate both the steady-state and the dynamic flow control characteristics at constant pressure of a model (32.7 in. diameter) double-inlet, double-width centrifugal blower at low tip speed (~250 ft/s). The impeller was designed with fixed backward-curved jet-flap airfoil blades and the housing was equipped with rotatable jet-flap inlet guidevanes. The flow control test was carried out at constant pressure, starting from the maximum efficiency (85%) point of the basic blower. Over 50% negative flow control was achieved with the jet-flap inlet guidevanes and 50% positive flow control was obtained with the impeller jet-flap, with a jet-flap supply flow of only 2.8%. Frequency response tests were carried out on the impeller jet-flap flow control system with a rotating butterfly. The pressure amplitude ratio was found to remain above −3 dB for all frequencies tested, up to the maximum 12.5 Hz, where the phase angle approached 90 deg.**

## Nomenclature

| | |
|---|---|
| $a_1$ | = blower output pressure amplitude at variable frequency, psf |
| $a_1{}^*$ | = quasisteady output pressure amplitude, psf |
| $a_2$ | = blower jet-flap input pressure amplitude at variable frequency, psf |
| $a_2{}^*$ | = quasisteady input pressure amplitude, psf |
| $b$ | = blade tip width, ft |
| $C_\mu = \dot{m}V_j/\frac{1}{2}\rho u^2 S$ | = slot momentum coefficient |
| $C$ | = blade chord, ft |
| $D$ | = impeller diameter, ft |
| $\dot{m}$ | = total slot mass flow, lb-s/ft |
| $N$ | = impeller rotational speed, rev/s |
| $P_s$ | = static pressure rise, psf |
| $P_T$ | = total pressure rise, psf |
| $P_j$ | = jet-flap supply static pressure, psf |
| $Q$ | = blower output flow, $ft^3/s$ |
| $Q_j$ | = jet-flap supply flow, $ft^3/s$ |
| $r = a_1 a_2{}^*/a_1{}^* a_2$ | = output/input normalized pressure amplitude ratio |
| $S = b \cdot C$ | = nominal blade area, $ft^2$ |
| shp | = shaft horsepower, ft-lb/s |
| $V_j$ | = slot velocity, ft/s |
| $u$ | = $\pi DN$ = impeller tip speed, ft/s |
| $\phi$ | = $Q/\pi/4D^2 u$ = blower flow coefficient |
| $\phi_j$ | = $Q_j/\pi/4D^2 u$ = jet-flap flow coefficient |
| $\psi_s$ | = $P_s/\frac{1}{2}\rho u^2$ = blower static pressure coefficient |
| $\psi_T$ | = $P_T/\frac{1}{2}\rho u^2$ = blower total pressure coefficient |
| $\psi_j$ | = $P_j/\frac{1}{2}\rho u^2$ = jet-flap supply static pressure coefficients |
| $\eta_s$ | = $Q \cdot P_s$/shp = blower static efficiency |
| $\eta_T$ | = $Q \cdot P_T$/shp = blower total efficiency |

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Index categories: Ground Effect Machines; Rotating Machinery; Marine Vessel Systems, Submerged and Surface.

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## Introduction

THERE is general agreement[1-4] that the lifting air-cushion system may require an active flow control loop to minimize craft accelerations in heave and pitch, to maintain velocity, and to prevent pressure pulsations and consequent structural fatigue failures, depending upon the intended operational environment of speed, wind, and sea state. The development of such a flow control loop requires the understanding of the dynamic characteristics of the system, as well as of the components, and also experience in closed-loop operation. A comprehensive review of fan dynamic response is given by Moran.[5] A theoretical and experimental investigation of the frequency response of blower/duct/plenum systems is presented by Goldschmied and Wormley.[6] The dynamic response of motor/blower/plenum systems has been studied by Durkin and Luehr.[7] Hinchey and Sullivan[8] also have investigated the duct effects on the dynamic fan characteristics of air-cushion systems. For closed-loop flow control operation, there seems to be available only the work of Allison and Hope-Gill[9] and Durkin[10]; the former authors achieved 36 to 85% pressure fluctuation reduction up to 2.5 Hz, while the latter achieved 25 to 60% up to 2.0 Hz.

Both positive and negative flow control at constant pressure and at constant rpm would be required for the lift blowers, to an estimated ±50% range. Flow control of centrifugal blowers is well-established in the industry in regard to steady-state performance and efficiency. The most obvious means of changing flow is by changing blower rpm, since the flow is directly proportional to rpm for a constant system resistance; however, for constant pressure, the flow/rpm relationship also depends upon the shape of the performance curve and becomes much more complex. Furthermore, the rpm change cannot be achieved quickly because of the inertia of the blower/driver rotating masses. Schneider and Kaplan[11] have carried out a theoretical investigation of the dynamics of blower rpm changes for surface-effect ships, on the basis of quasisteady fan performance.

Negative flow control, i.e., decreasing blower flow at constant rpm, by inlet guidevanes has been standard practice in the U.S. centrifugal blower industry for 40 years; the invention is due to H.F. Hagen and patents were issued in 1932[12] and 1935.[13] An improvement was patented by J. E. McDonald in 1958.[14] Voluminous steady-state performance data[15,16] are available but no frequency response or step-response data could be found, although individual electrohydraulic actuation of the inlet guidevanes is entirely

**Table 1 Dimensionless performance table of 4132-D DWDI blower (144 in. diam) at 300 rpm**

| Flow coefficient, $\phi$ | Static pressure coefficient, $\psi_S$ | Total pressure coefficient, $\psi_T$ | Static efficiency, $\eta_S$, % | Total efficiency, $\eta_T$, % |
|---|---|---|---|---|
| 0 | 0.962 | 0.962 | —... | —... |
| 0.129 | 1.06 | 1.070 | 75.81 | 76.18 |
| 0.176 | 1.07 | 1.076 | 85.51 | 86.28 |
| 0.202 | 1.07 | 1.080 | 87.29 | 88.30 |
| 0.202 | 1.07 | 1.090 | 88.53 | 89.56 |
| 0.217 | 1.05 | 1.060 | 88.43 | 89.65 |
| 0.217 | 1.05 | 1.065 | 88.25 | 89.46 |
| 0.242 | 0.989 | 1.01 | 87.81 | 89.40 |
| 0.270 | 0.932 | 0.955 | 87.91 | 90.00 |
| 0.273 | 0.912 | 0.936 | 86.98 | 89.17 |
| 0.315 | 0.776 | 0.806 | 82.75 | 86.02 |
| 0.355 | 0.676 | 0.692 | 76.49 | 81.04 |
| 0.356 | 0.664 | 0.704 | 75.38 | 79.72 |

practical for fast negative flow control.

A novel negative flow control method was developed by the Aerojet Liquid Rocket Co.[17] based upon a sleeve moving axially in and out of the blower inlet. A test of a 24 in. diameter double-inlet, double-width model at 3500 and 2800 rpm is reported by Durkin.[10] The maximum total efficiency was 65%, with the sleeve completely retracted; the flow coefficient was $\phi = 0.29$ and the total pressure coefficient was $\psi_T = 0.73$. At constant pressure, the negative flow control was $\Delta\phi/\phi = 75\%$, with a terminal total efficiency of 39% and the sleeve at the 25% open position. This sleeve mechanism produced a nonlinear effect, since there was little flow change between the 75% open and the 50% open sleeve positions.

Positive flow control (i.e., increasing blower flow at constant rpm) has not yet been adopted in the U.S. blower industry, although it offers great potential for energy savings. It requires increasing the aerodynamic circulation around the impeller blades by mechanical means such as rotatable flaps or tips or by fluid means such as "controlled-circulation" or "jet-flap."

Goldschmied[18] invented and patented what is today known as the "controlled-circulation" centrifugal blower. Recently Furey and Whitehead[19] presented the results of a preliminary experimental investigation of a single-inlet, single-width, controlled-circulation blower model. Blowing slot details were not disclosed, however. The impeller diameter was 24 in. and the speed 2200 rpm, with a tip speed of 230 ft/s. The blade tip width was 5.0 in., with consequent width/diameter ratio of 0.208; this yields high structural risks for anticipated design tip speeds up to 600 ft/s.†

The 14-blade blower, at its best efficiency point in the better housing, had a flow coefficient $\phi = 0.15$, a total pressure coefficient $\psi_T = 0.83$, and a total efficiency $\eta_T = 74\%$. Keeping constant pressure, a flow gain $\Delta\phi/\phi = 77\%$ was achieved with a blowing momentum coefficient $C_\mu = 0.068$ and sonic slot flow. The terminal efficiency, including the air supply power, was 42%.

The seven-blade blower, at its best efficiency point in the better housing, had a flow coefficient $\phi = 0.19$, a total pressure coefficient $\psi_T = 0.66$, and a total efficiency of 76%. At constant pressure, a flow gain $\Delta\phi/\phi = 50\%$ was achieved with a blowing momentum coefficient $C_\mu = 0.045$. The terminal efficiency, including air supply power, was 60%.

The maximum blowing air supply (at $C_\mu = 0.065$) was approximately 3% of the flow at the maximum efficiency point. Unfortunately, the testing did not conform to AMCA Standard 210-74[21] and thus it is not possible to assess this performance exactly against other centrifugal blowers. The efficiency difference between the AMCA[21] test method and the test methods of Ref. 19 could be as much as 5%. Goldschmied[22] also invented and patented the "jet-flap" centrifugal blower; an experimental investigation of the steady-state performance of such a blower was presented later by Goldschmied,[23] using a high-efficiency (88%), single-inlet, single-width 30 in. diameter model at 1200 rpm, with a safe width/diameter ratio of 0.133. Blowing momentum coefficients up to $C_\mu = 0.017$ were employed. No dynamic flow control test data were presented either in Ref. 19 or Ref. 23 for complete centrifugal blowers. For single airfoils, the work of Deal[24] and Lancaster[25] investigated the unsteady aerodynamics of a circulation-controlled airfoil response.

Positive flow control by mechanical rotatable blade tips was investigated experimentally by Goldschmied[23] with excellent aerodynamic results. The problem, of course, is the reliable mechanical or hydraulic actuation of the blade tips.

Positive flow control by mechanically controllable variable-camber blades was investigated by Allison and Hope-Gill,[9] achieving 36% flow increment at constant pressure.

The present investigation was motivated by the need of a complete quantitative investigation of both steady-state and dynamic performance of a double-inlet, double-width, centrifugal jet-flap blower to provide the exact design basis for general air-cushion application.

## Test Installation

The centrifugal jet-flap blower used in this test program was based upon an industrial Westinghouse double-inlet, double-width, backward-curved airfoil design; only the blade trailing edge was thickened to accommodate the jet-flap slot and its air supply. The industrial blower had the denomination of 4132-D DWDI, with a 144 in. diameter impeller. It was shop tested at 300 rpm (~ half-speed) in 1973 prior to delivery to the customer for powerplant application; the dimensionless performance data are given in Table 1. It is seen that the total efficiency exceeded 89% over a broad flow range and the static efficiency exceeded 87% over the same range.

In Fig. 1 the 32.75 in. diameter blower is shown installed on the test stand with a torque meter and a 100 hp 1750 rpm ac motor. The housing and the inlet cones are cast aluminum and very rigid to allow meaningful dynamic pressure measurements. The impeller shaft is hollow at the left-hand end to receive the external jet-flap air supply.

In Fig. 2 there are shown the mechanically rotatable jet-flap inlet guidevanes mounted in the blower inlet; to be noted that the jet-flap air supply is provided to each hollow vane directly from the blower housing, thus establishing a *negative feedback loop* for decreasing flow control. The jet-flap slot design was similar to that shown in Fig. 3 for the rotor blades. In the

†Structural rotor safety cannot be overemphasized, as demonstrated in May 1977 by the extensive cracking of welds discovered on all eight lift fan rotors of the JEFF-A craft after the first checkout run at 513 ft/s tip speed; this was reported by Brown and Bullock.[20]

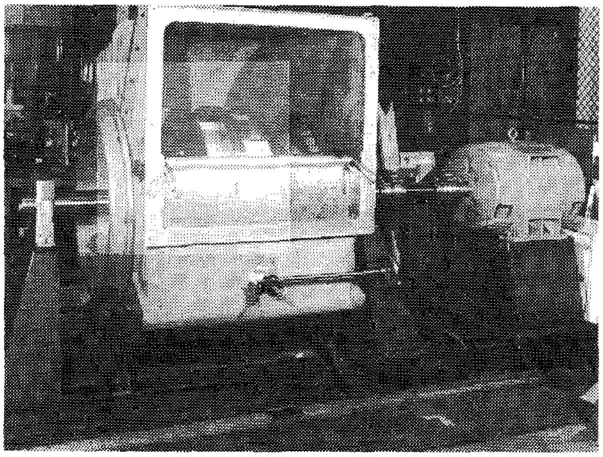


Fig. 1 Side view of blower assembly on test stand with torque meter and motor drive.

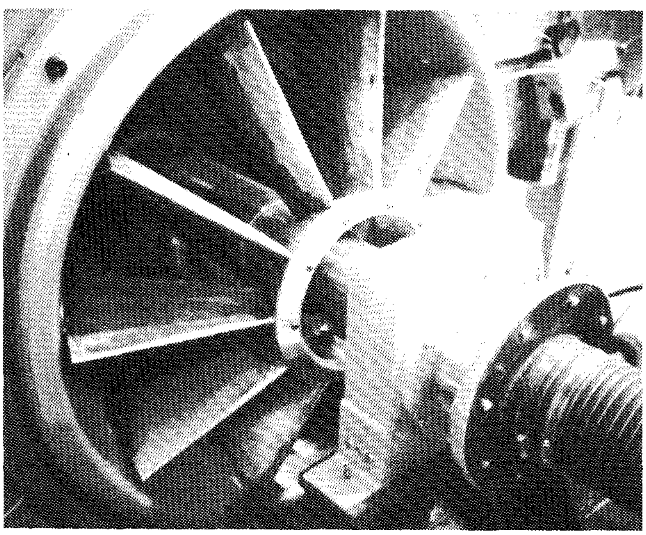


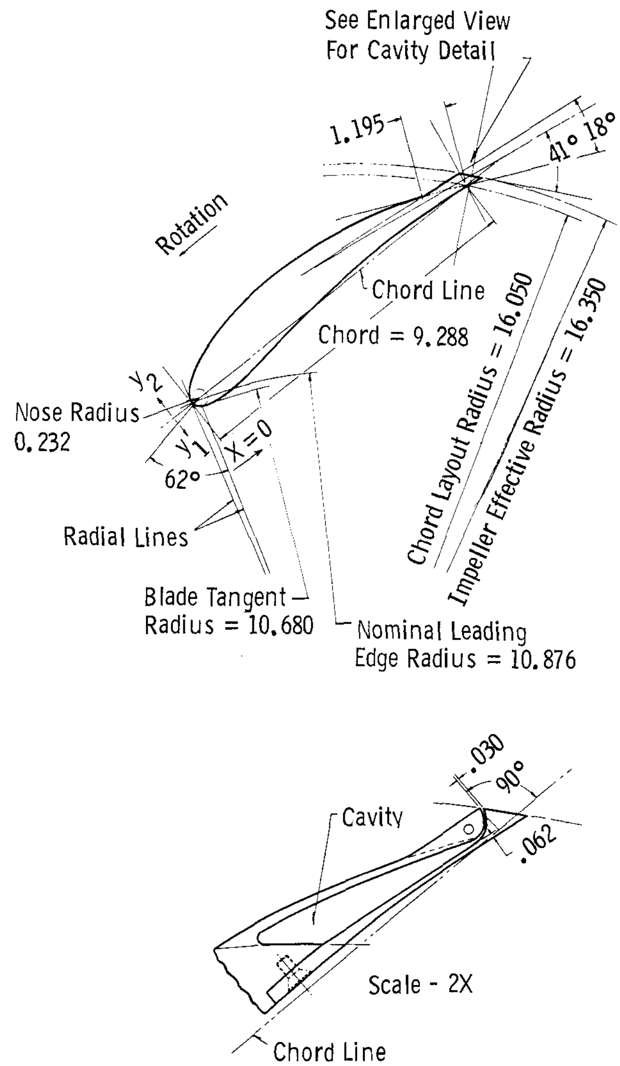
Fig. 2 Jet-flap inlet guidevanes.

test program, for simplicity, this air supply was either fully on or fully off. Also to be noted in Fig. 2 is the flexible hose bringing the external air supply into the blower's hollow shaft to actuate the jet-flap of the impeller blades. This external jet-flap supply pressure was *measured just ahead of the bearing block* and its mass flow was measured upstream by a 4 in. diameter ASME nozzle. Thus, the air supply power was exactly determined and it was used for the overall blower efficiency computation. For the inlet guidevanes, the jet-flap air supply was purely internal (from housing to vanes) and it was not measured.

In Fig. 4 there is shown the 32.75 in. diameter double-inlet, double-width aluminum impeller; the 20 blades were completely machined and were assembled with fitted through bolts without any welding. The thick centerplate was required to accommodate the air-supply plenum and it probably caused some small aerodynamic loss. The jet-flap 0.030 in. slots are clearly visible, spanning the entire 5.25 in. blade trailing-edge width.

The blade layout is shown in Fig. 3 and the housing layout is given in Fig. 5. It can be seen that the cutoff sheet is hinged and adjustable, so that best performance may be obtained at each flow condition. Small cutoff sheet adjustments can result in total efficiency changes up to 4%; the fan noise radiation is also significantly affected by the cutoff position. Some flow control can also be achieved by the cutoff sheet actuation.

Finally, the external jet-flap supply arrangement is shown in Fig. 6, with a twin rotating-butterfly rig to provide




Notes:

1. 10 Blades Each Side
2. T.E. Blade Width @ 16.350 Radius = 5.25
3. $\frac{R_1}{R_2} = \frac{10.680}{16.350} = .653$

Fig. 3 Layout of jet-flap impeller blades.

sinusoidally pulsating flow, without stalling the small high-speed Paxton CB-90 air compressor. The butterfly speed could be controlled at 10 to 400 rpm by a variable hydraulic drive.

The steady-state blower performance testing was conducted in accordance with Fig. 7 of AMCA Standard 210-74.[21] The dynamic frequency response test of the impeller jet-flap flow control does not fall within the domain of Standard 210-74 or any other recognized standard as yet.

## Steady-State Performance

The basic test of the blower, with open inlets (inlet guidevanes not installed) and zero jet-flap supply (closed) is shown in dimensionless format in Fig. 7; the total pressure coefficient $\psi_T$ and the total efficiency $\eta_T$ are plotted against the flow coefficient $\phi$. In the same figure there is also plotted the performance of the geometrically similar 144 in. diameter industrial blower. It is clear that the efficiency of the test

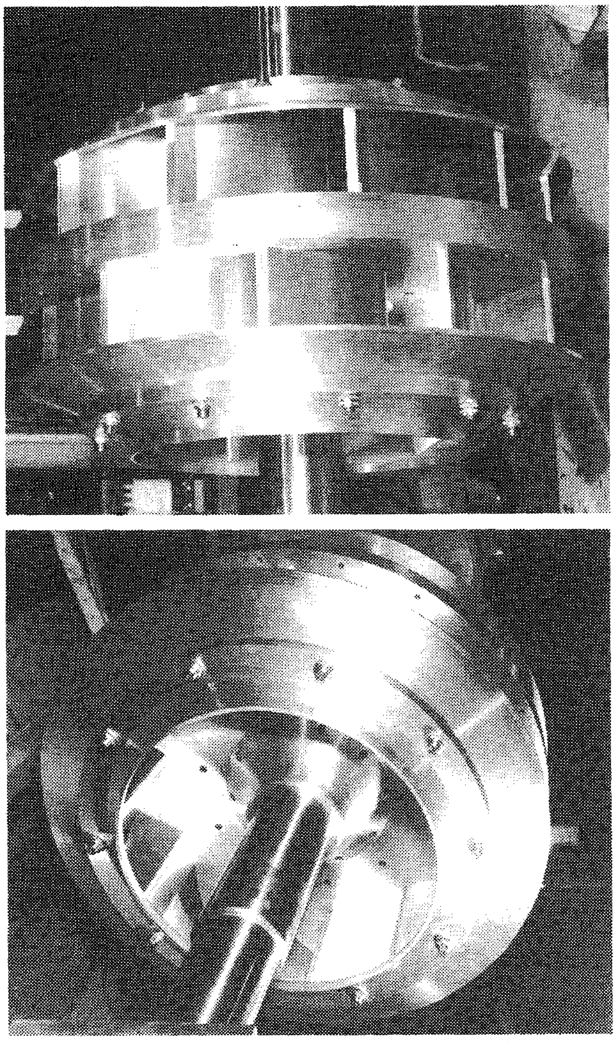

a)
b)

Fig. 4 Jet-flap double-inlet, double-width centrifugal impeller.

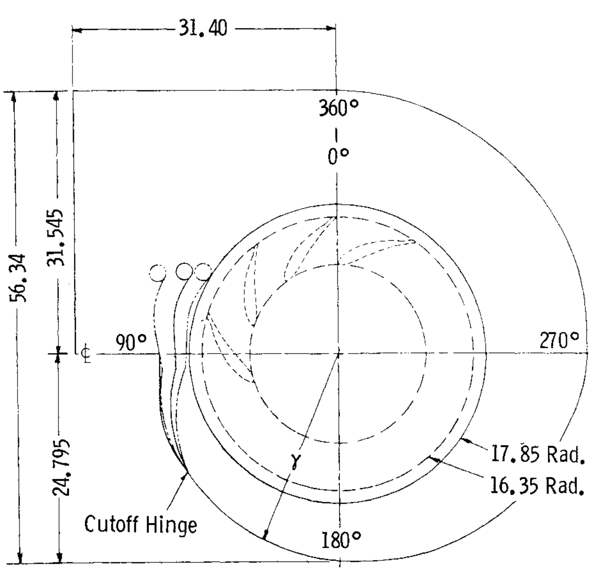



Fig. 5 Layout of blower housing.

model is ~4 points lower from the design point all the way to maximum flow. From maximum flow up to stall the pressure points happen to coincide, but the model has a sharper stall; at shutoff, again the pressures coincide. The efficiency difference may be partly due to Reynolds number effects but it is also caused by the aerodynamic impeller design compromises required by the jet-flap slot and supply constraints, i.e., thick

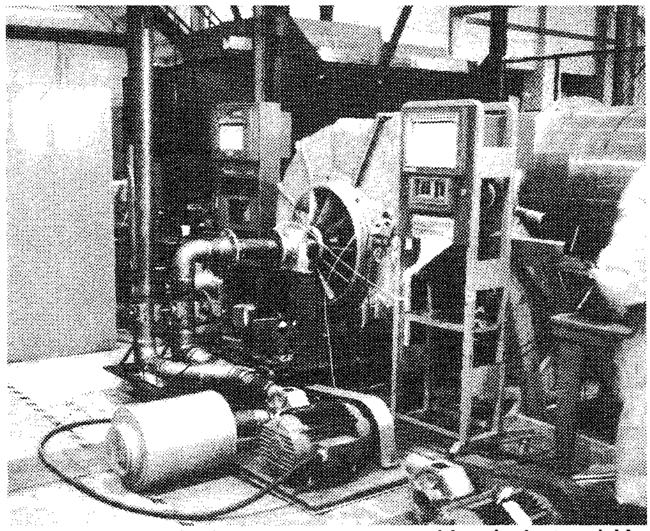


Fig. 6 Dynamic jet-flap test arrangement with twin-duct variable-speed rotating-butterfly rig.

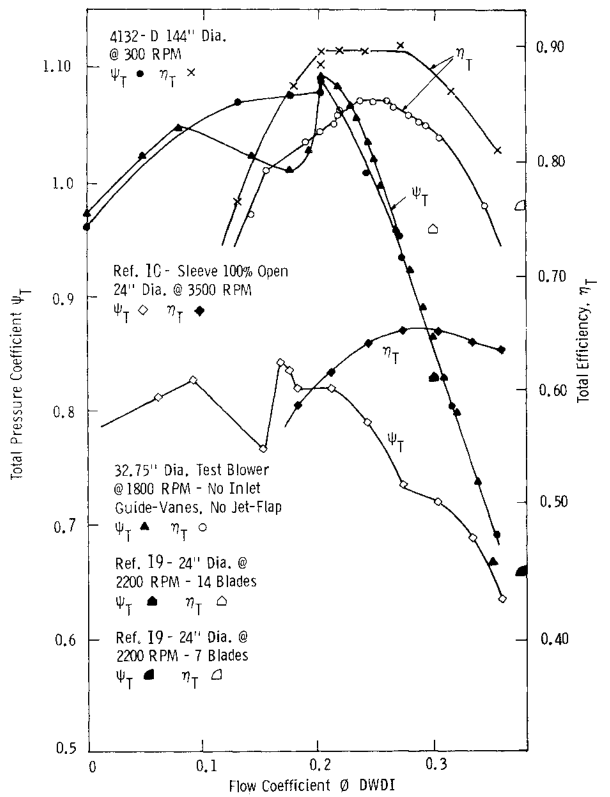



Fig. 7 Steady-state performance of basic test blower.

blade trailing edges and thick impeller centerplate. On Fig. 7 there is also plotted for reference the experimental performance of the variable-geometry blower from Ref. 10, for the fully open sleeve position. It is seen that both pressure coefficient and efficiency are much lower than the present test unit. Also shown are the maximum efficiency points for the 24 in. diameter 14-blade blower at 2200 rpm and for the 7-blade blower, both with the better housing, from Ref. 19. It is seen that both pressure points fall on the pressure curve of the test unit, while the maximum efficiencies are lower. Comparing the pressure/flow curve of Fig. 7 for the 32.75 in. diameter test blower with no jet-flap and no inlet guidevanes with the corresponding curve of Fig. 8 with no jet-flap but with inlet guidevanes, it can be noted that the addition of inlet guidevanes delays the stall to higher pressures and also prevents a sharp stall. This effect is due to the inlet guidevanes stopping the prerotation of the fan inlet flow.

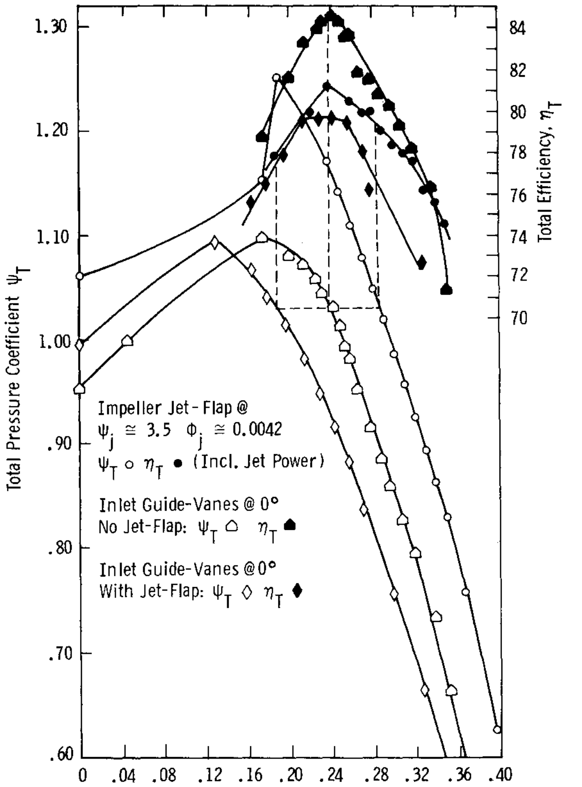



**Fig. 8 Steady-state ±20% flow control performance.**

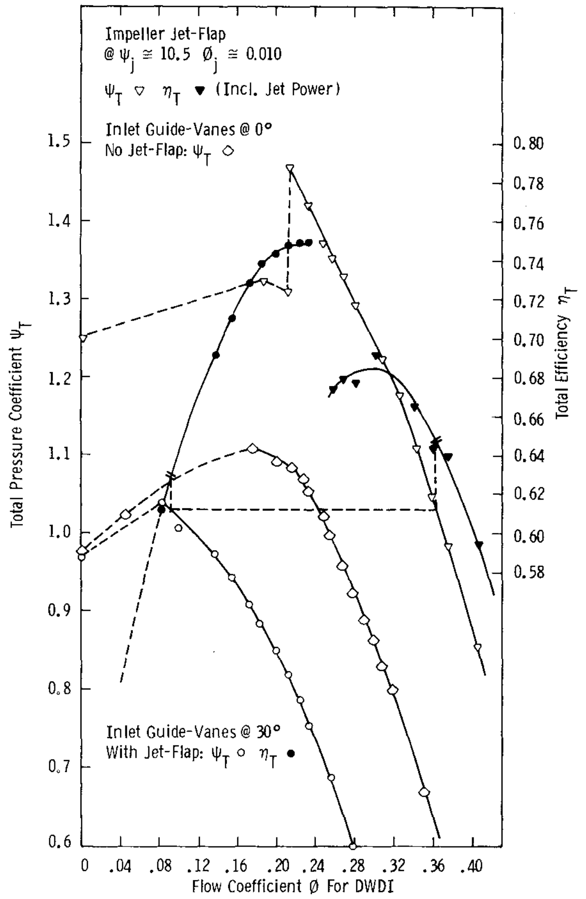



**Fig. 9 Steady-state +50%, −62% flow control performance.**

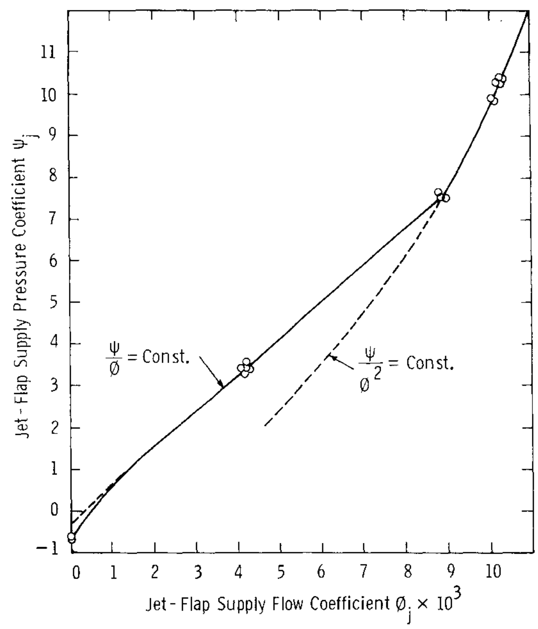



**Fig. 10 Impeller jet-flap supply pressure/flow plot.**

The first goal of the investigation was to achieve ±20% flow control, at constant pressure and rpm, by purely aerodynamic means, i.e., jet-flap. Figure 8 shows three performance curves. The middle curve is that of the basic blower, with inlet guidevanes set at 0 deg (fully open) and jet-flap slots closed, and with impeller jet-flap supply closed. The lower curve corresponds to the case where the inlet guidevanes had "feedback" jet-flap while the impeller had the jet-flap supply closed. The upper curve corresponds to the case where the inlet guidevanes had closed slots and the impeller had the jet-flap air supply partly open.

If a constant pressure line is drawn at $\psi_T = 1.03$ through the best efficiency point of the basic blower, it is plainly seen that the flow control occurs from $\phi_0 = 0.24$ ($\eta_T = 84.5\%$) down to $\phi = 0.19$ ($\eta_T = 77.5\%$) or $-21\%$ and up to $\phi = 0.288$ ($\eta_T = 79.4\%$) or $+20\%$. It is to be well noted that the external jet-flap air power was included in the efficiency computation. The worst efficiency in the ±20% control range was better than the maximum efficiencies in Refs. 10 and 19.

The second goal of the investigation was to achieve ±50% flow control at constant pressure and rpm. Figure 9 shows three performance curves. The middle curve is that of the basic blower, with inlet guidevanes set at 0 deg (fully open) and jet-flap slots closed, and with jet-flap supply closed. The lower curve corresponds to the case where the inlet guidevanes were mechanically set at 30 deg and had "feedback" jet-flap, while the impeller had the jet-flap supply closed. The upper curve corresponds to the case where the impeller had the maximum available jet-flap supply (corresponding to an average momentum coefficient $C_\mu \sim 0.045$), while the inlet guidevanes were set at full-open position (0 deg) with the jet-flap slots closed.

If the same constant pressure line is drawn at $\psi_T = 1.03$ through the best efficiency point ($\eta_T = 84.5\%$) of the basic blower, it is plainly seen that the flow control range starts at $\phi = 0.092$ ($\eta_T = 63\%$) and ends at $\phi = 0.362$ ($\eta_T = 64.7\%$). The negative flow control is $-62\%$ and the positive flow control is $+49.5\%$. Again, the external jet-flap supply power was included in the efficiency calculation.

It is of great interest to present the impeller jet-flap air supply performance, i.e., dimensionless supply pressure coefficient (measured just ahead of the bearing block, see Fig. 2) vs dimensionless flow coefficient. This is shown in Fig. 10. At the maximum flow, the average momentum coefficient is $C_\mu \simeq 0.045$; this value compares equally to the results of Ref. 19 for the "controlled-circulation" blower, for the same $\sim 50\%$ flow gain. In terms of the basic blower flow output ($\phi_0 = 0.24$), the ratio $\phi_j / \phi_0 = 0.010/0.24 = 4.1\%$ but in terms

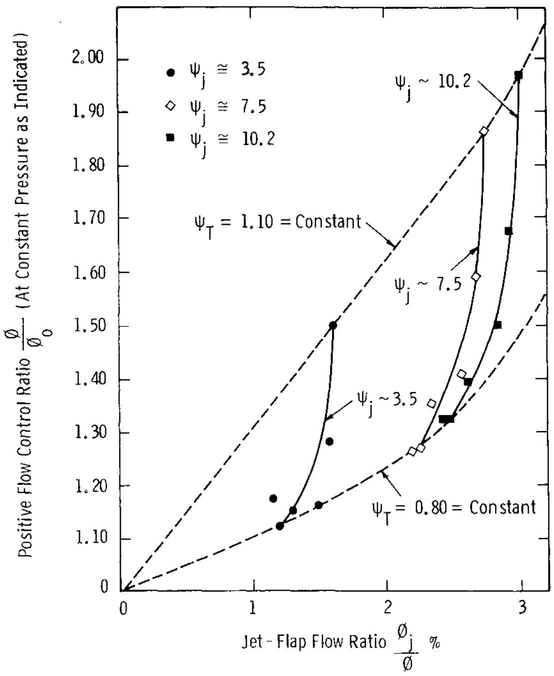



**Fig. 11 Impeller jet-flap positive flow control map.**

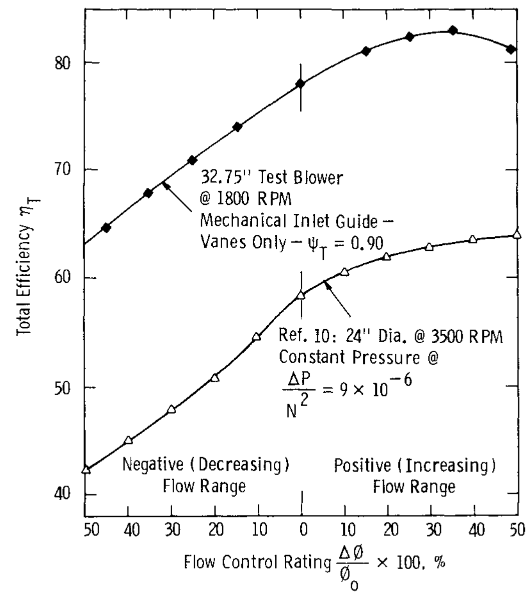



**Fig. 12 Comparison of mechanical flow control methods.**

of the augmented output flow, the ratio becomes $0.010/0.362 = 2.75\%$.

In terms of pressure, it is to be noted that the maximum (stall) pressure coefficient of the basic blower is $\psi_T \simeq 1.1$ while, with full jet-flap, it becomes $\psi_T \simeq 1.50$. Thus a maximum supply pressure coefficient $\psi_j \sim 10$ signifies 6.6 times the maximum blower output; this is an indication of the control gain.

From the point of view of power efficiency, the jet-flap supply should not exceed the linear $\psi_j - \phi_j$ range, i.e., $\psi_j = 7.5$, since beyond that point the pressure increases as the square of the flow. It is to be understood that the linear range is due to the resistance being counteracted by the pumping action of the spinning rotor upon the jet-flap supply flow itself; when this flow becomes too large, the resistance predominates over the pumping.

Figure 11 presents a map of the impeller jet-flap positive flow control, in terms of output flow ratio $\phi/\phi_0$ against jet-flap flow ratio $\phi_j/\phi$. The map is bounded by an upper curve representing constant pressure at $\psi_T = 1.10$ and by a lower curve representing constant pressure at $\psi_T = 0.80$.

Lines of constant jet-flap supply pressure are drawn between the upper and lower bounds, for $\psi_j \simeq 3.5$, $\sim 7.5$, and $\sim 10.2$. The output flow ratio is a strong function of the $\psi_T$ value chosen for the constant pressure; for maximum supply pressure ($\psi_j \sim 10.2$) it can vary from $\sim 2.0$ down to $\sim 1.3$.

Finally, it is of some interest to compare the mechanical negative flow control performance of Ref. 10 with that obtained by mechanical inlet guidevanes rotation without jet-flap (slots closed). Since $\pm 50\%$ flow control is still required, the "basic" blower is now taken to be at a 45 deg inlet guidevane setting and at a reduced flow coefficient $\phi = 0.185$, so that positive flow control can be claimed simply by resetting the inlet guidevanes to 0 deg and achieving the original blower performance ($\phi = 0.28$). The output pressure coefficient level had to be dropped from $\psi_T = 1.03$ to 0.90 for this application. For a given flow and pressure, the blower diameter will have to be larger by $\sim 15\%$ or $\sqrt{0.28/0.185}/\sqrt{1.03/0.90}$.

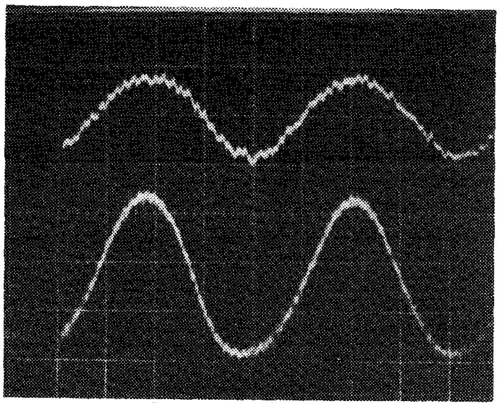
Figure 12 presents this comparison in terms of total efficiency $\eta_T$ against flow control rating $\Delta\phi/\phi$. It is seen that the new "basic" efficiency is 78% for the present unit and 58.4% for Ref. 10. Since the air-cushion vehicle is supported by air pressure, weight minimization is mandatory. Therefore, it is difficult to see why this flow control method would be used, since the lift fan weight would be increased by $\sim 40\%$ (because of the 15% larger diameter) and the lift fuel weight would be increased over 10% (using the Westinghouse fan).

## Frequency Response

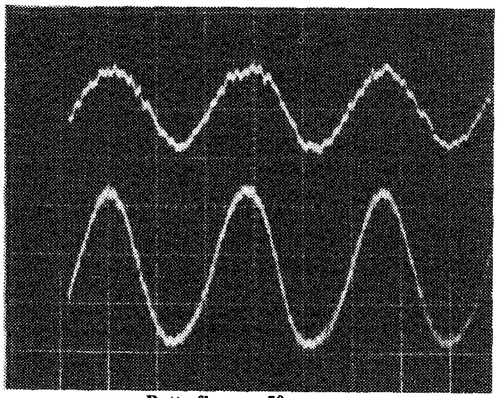
A frequency response test was carried out for the impeller jet-flap flow control, by modulating sinusoidally the supply

**Table 2 Frequency response test**

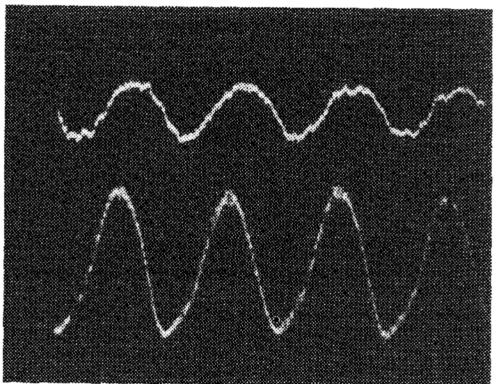
| Butterfly, rpm (counter) | Frequency, Hz (oscilloscope) | Output pressure ratio, $a_1/a_1{}^*$ | Input pressure ratio, $a_2/a_2{}^*$ | Phase angle, deg | Output ratio / Input ratio |
|---|---|---|---|---|---|
| 10 | 0.25 | 1.0 | 1.0 | 7.5 | 1.0 |
| 25 | 1.19 | 1.0 | 1.0 | 20 | 1.0 |
| 50 | 1.78 | 1.0 | 1.0 | 25 | 1.0 |
| 70 | 2.44 | 1.0 | 1.0 | 29 | 1.0 |
| 75 | 2.56 | 1.0 | 1.0 | 25.5 | 1.0 |
| 100 | 3.33 | 1.0 | 0.967 | 27 | 1.03 |
| 150 | 5.00 | 1.0 | 0.967 | 30 | 1.03 |
| 200 | 6.66 | 0.937 | 0.938 | 40 | 1.0 |
| 220 | 7.40 | 0.875 | 0.938 | 45 | 0.932 |
| 250 | 8.70 | 0.75 | 0.938 | 52 | 0.80 |
| 300 | 10.0 | 0.688 | 0.907 | 63 | 0.76 |
| 350 | 11.9 | 0.688 | 0.875 | 74 | 0.785 |
| 400 | 12.5 | 0.688 | 0.875 | 87 | 0.785 |



**Butterfly rpm: 25**
**Vertical scale: 0.2 V/cm**
**Horizontal scale: 0.2 s/cm**
**Output amplitude: 0.32 V**
**Input amplitude: 0.64 V**
**Period: 0.84 s**



**Butterfly rpm: 50**
**Vertical scale: 0.2 V/cm**
**Horizontal scale: 0.2 s/cm**
**Output amplitude: 0.32 V**
**Input amplitude: 0.64 V**
**Period: 0.56 s**



**Butterfly rpm: 250**
**Horizontal scale: 0.05 s/cm**
**Vertical scale: 0.2 V/cm**
**Output amplitude: 0.24 V**
**Intput amplitude: 0.60 V**
**Period: 0.115 s**

**Fig. 13 Oscilloscope photos of frequency response test of impeller jet-flap at $\psi_j = 5.0$ and 1790 rpm.**

pressure and by recording the blower output pressure at the housing's discharge. Unfortunately, no frequency response test could be carried out for the inlet guidevanes jet-flap flow control because of termination of project funding. A Setra Model 237 pressure transducer was mounted at the discharge of the cast aluminum blower housing and another similar instrument was mounted just ahead of the bearing block (see Fig. 2) in the air supply line. The two electrical outputs were displayed together on an oscilloscope and photographed. The

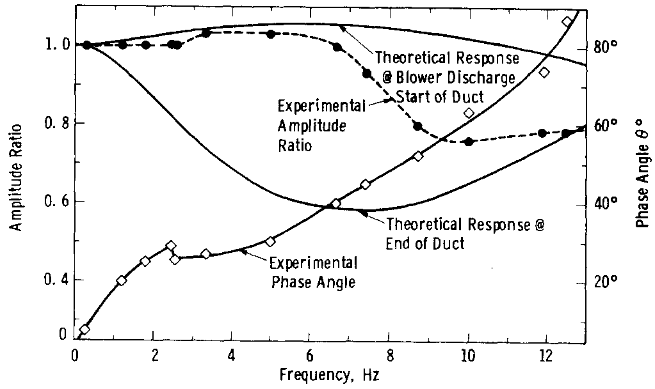



**Fig. 14 Frequency response of impeller jet-flap positive flow control.**

butterfly speed was varied from ~10 to ~400 rpm, with frequencies of 0.25 to 12.5 Hz. A mechanical rpm counter was used for butterfly speed setting, but the exact frequency was obtained from the oscilloscope photos. The blower's load was kept in steady-state at the best efficiency point.

A summary of the results is given in Table 2 and a sample set of oscilloscope photos is given in Fig. 13. The top channel is the blower pressure output, and the bottom channel is the jet-flap supply pressure input. The blower rpm was 1790 and the peak pressure input corresponded to $\psi_j \sim 5.0$ for all tests. It is to be noted that the input also decreased as the frequency increased; thus the output had to be corrected accordingly. The output/input ratio is plotted against frequency in Fig. 14, together with the theoretical response. This response has been computed for the blower/duct test system by the method of Goldschmied and Wormley.[6] There is excellent agreement between test and theory up to ~7 Hz and then the test data drop lower and hold at a level of ~0.8. This discrepancy has not yet been investigated. The phase angle increases with frequency and reaches ~90 deg at 12.5 Hz (maximum test frequency).

## Conclusions

Several significant conclusions may be drawn from the test results of this investigation:

1) Flow control of ±20% at constant pressure has been achieved by purely aerodynamic means, so as to maximize the frequency response of the flow control method. The lowest efficiency was 77.5% at −21%.

2) Flow control of ±50% at constant pressure has been achieved by mixed aerodynamic and mechanical means. The maximum mechanical motion required is the 30 deg rotation of the inlet guidevanes. The lowest efficiency was 63% at −62%.

3) The largest momentum coefficient $C_\mu$ at the impeller jet-flap slot had a value of 0.045. This compares with maximum values of 0.068 employed by Furey and Whitehead[19] for their controlled-circulation blower.

4) A frequency response of 12.5 Hz has been achieved for the impeller jet-flap, above −3 dB pressure amplitude; a comparable response is expected for the inlet guidevanes feedback jet-flap.

5) The total efficiency of the present blower with only purely mechanical inlet guidevanes is superior to that of the variable-geometry unit tested by Durkin[10] over the entire ±50% flow control range.

6) Maximum model efficiency of 84.5% compares very well with the 74 and 76% of Ref. 19 and with the 64% of Ref. 10.

It is recommended that further development work be undertaken on the feedback jet-flap inlet guidevanes to improve their effectiveness and also on a feedback system for the jet-flap rotor blades. A purely feedback jet-flap system would avoid the need of external jet-flap air supply sources.

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