A TEST PROGRAM TO MEASURE FLUID MECHANICAL

WHIRL-EXCITATION FORCES IN CENTRIFUGAL PUMPS

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ABSTRACT

Much speculation has surrounded the possible unsteady hydrodynamic forces which could be responsible for the excitation of whirl instabilities in turbomachines. However there exist very few measurements of these forces which would permit one to evaluate the merits of the existing fluid mechanical analyses. In keeping with the informal nature of this workshop we will present details of a proposed test program for the measurement of the unsteady forces on centrifugal impellers caused by either (i) azimuthal asymmetry in the volute geometry or (ii) an externally imposed whirl motion of the impeller. In the second case the forces resulting from the imposed whirl motions with frequencies ranging from zero to synchronous will be measured by means of a force balance upon which the impeller is mounted. This work is presently being carried out under contract with the NASA George Marshall Space Flight Center, Huntsville, Alabama (Contract NAS 8-33108).

INTRODUCTION

In recent years it has been increasingly recognized that hydrodynamic cross-coupling forces can cause serious rotor dynamic problems in high speed turbomachines. Such problems have been experienced not only in steam turbines (Refs.1,2), but also in large compressors (Refs. 3,4) and in high speed pumps (Ref. 5). Though other instability mechanisms such as internal damping or non-isotropic shaft stiffness rotor inertia can be fairly readily characterized the same cannot be said of the hydrodynamic cross-coupling forces. Various hydrodynamic flows have been identified as possible contributors to these destabilizing forces. Bearings and particularly seals can clearly play such a role as the papers in this volume attest. But much less is known about the potential for destabilizing forces arising from the flows associated with the impeller and diffuser of a compressor or pump; this brief paper will be confined to this issue.

The flow associated with the impeller/diffuser is significantly different from that in a seal or bearing in that the geometry of the volute can cause this flow to be significantly non-axisymmetric. The work of Domm and Hergt (Ref. 6) has shown that this could give rise to a lateral force on the impeller even in the absence of an orbiting motion of the shaft. They derived magnitudes for this stationary lateral force based on a source vortex model for the impeller. In an actual impeller this lateral force may also contain

an unsteady component at the blade passage frequency though the magnitude of this unsteady force and the role it might play in the rotor dynamics has not yet been determined. More realistic impeller models would be required for this purpose.

Recently Colding-Jorgensen (Ref. 7, see also this volume) has extended the work of Domm and Hergt. Imposing an orbiting motion on the source/vortex model of the impeller, he analyzed the resulting radial and tangential forces on the "impeller" and found that positive or whirl excitation tangential forces did indeed result from such an analysis and that the magnitudes of these forces were sufficient to have played a significant role in the Space Shuttle high pressure hydrogen pump instability (Ref. 5). However the main question here is the validity of the simple source/vortex model used for the impeller; further analyses with more realistic impeller models will be required in order to determine the limits of validity of such analyses. One useful intermediate model which is still fairly simple is the actuator disk which has been suggested by the work of Chamieh and Acosta (Ref. 8,9).

Other analyses have sought destabilizing tangential forces in the absence of volute asymmetries. Here we have two possible mechanisms which have been suggested. In an addenda to his paper on whirl-excitation forces in seals, Alford (1965) suggested that the same mechanism would occur in the tip clearance flows of steam turbines and others have further extrapolated this to the tip clearance flows in any turbomachine. The supposition is that a localized reduction in the tip clearance would cause a localized decrease in the torque shear stress with the reverse occurring on the other end of the diameter. This would lead to a positive or whirl-exciting tangential force.

Secondly, Thompson (Ref. 3) has posed the question of whether such a force would arise due to the perturbations imposed on the main flow through the impeller. Assuming quasi-static performance for each blade passage he used a detailed flow analysis program to assess the distribution of forces on the blades of an impeller performing whirling motions. Positive excitation did indeed occur with some impeller designs. It is not however clear whether the quasi-static assumption is valid in these circumstances.

Ultimately any review of the existing state of knowledge such as we have given above reveals a singular lack of hard experimental data with which to assess the merits of the various analyses. The primary purpose of this paper is to stress the fact that much remains to be done before the status of whirl-excitation forces on impellers can be put on a firm foundation. We are presently embarking on an experimental program whose intent is to measure these forces and the remainder of this paper is devoted to a brief description of this facility.

ROTOR FORCE TEST FACILITY

The objective of the facility is to impose known orbiting motions of frequency Ω on the basic rotary motion of a number of typical centrifugal pump impellers (rotating frequency, ω) and to measure the radial and tangential forces resulting from this motion. The core of the experiment is shown in
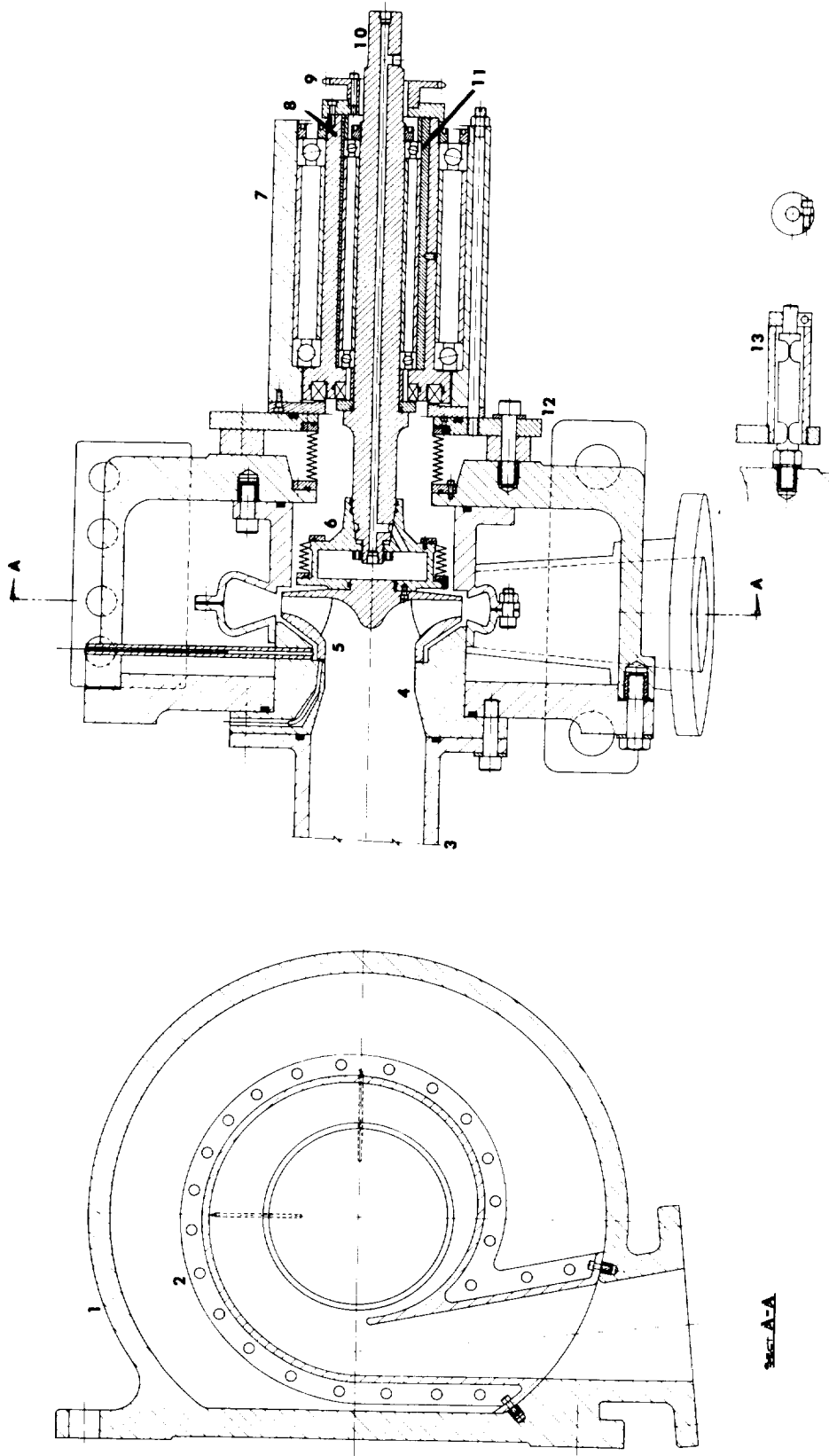
Figure 1. The impeller, volute, internal balance and eccentric drive of the Rotor Force Test Facility

231

Fig.1.The flow enters the centrifugal impeller(6)from the inlet connection(3)
and inlet bell(4). Volutes(2)of various geometries will be used in measure-
ments of lateral force due to volute asymmetry; they are contained in the pump
housing (1) so that they may be of lightweight construction. The impeller (5)
is mounted directly on an internal force balance (6). The main shaft (10)
rotates in a double bearing system (7,8,11) designed so that rotation of the
sprocket (9) causes the orbiting motion. In addition to the rotating internal
balance a back-up force measuring system(12,13)external to the eccentric drive
system will also be used. Figure 2, an overall schematic of the mechanical
system, shows the main drive system comprised of a 20HP variable speed motor,
a gear box and a flexible shaft (necessary to accommodate the orbiting motion).
This will be capable of speeds up to 35000 rpm ($\omega \to$ 60Hz.) Figure 2 also shows
the eccentric drive motor (2HP) which can generate orbit frequencies, Ω,
from 0 to 60 Hz.

Past experience with unsteady flow measurements has emphasized the need
for rigorous dynamic control of the experiments. In the present facility a
proximity probe senses the rotating frequency, ω; this signal is then used
to produce digital signals with frequencies $M\omega/N$, ω/N, $(N-M)\omega/N$ and
$(N+M)\omega/N$ where M and N are selected integers between 0 and 100 ($M \leq N$).
The signal at $M\omega/N$ is then used to drive the eccentric motor such that
$\Omega = M\omega/N$; a feedback control system fitted to this motor ensures accurate phase-
locking. In this way measurements can be made over a wide range of Ω/ω from
zero to unity.

Past experience has also indicated that the unsteady flow measurements
can be quite noisy and that accurate results require cross-correlation of
measurement and driving signal over many cycles. In the present case the
measurements may include (i) six-components of force measurement from the
internal balance or several components of force from the external balance (ii)
axial and radial displacement of the impeller from four fibre-optic displace-
ment probes (iii) pressure transducer measurements from locations both up-
stream and downstream of the impeller as well as within the impeller-volute
flow (iv) unsteady flow rate measurement using existing laser doppler veloci-
meters or electro-magnetic flow meters. A sixteen channel digital signal
processor is used for cross-correlation of these measurements with any of the
basic frequencies (ω,$M\omega/N$,ω/N,$(N-M)\omega/N$ and $(N+M)\omega/N$) in order to extract
the components of force at any of these fundamental frequencies
or higher harmonics thereof; this cross-correlation can cover up to 10,000
cycles of the fundamental frequency.

The most critical component in the system is probably the internal bal-
ance and its design is as yet unproven. One must ensure high natural fre-
quencies (>500Hz.) and yet maintain sufficient sensitivity. The present can-
didate design consists of four posts parallel with the axis which are mono-
lithic with two solid end plates, one attached to the shaft and the other at-
tached to the impeller. These posts are strain-gaged in such a way as to
extract all six force components with sensitivities of the order of mV/lb.

The hydraulic system into which this mechanical system is being installed
was previously utilized for measurements of the unsteady hydraulic performance
of cavitating (and non-cavitating) axial flow pumps (see, for example Refs.
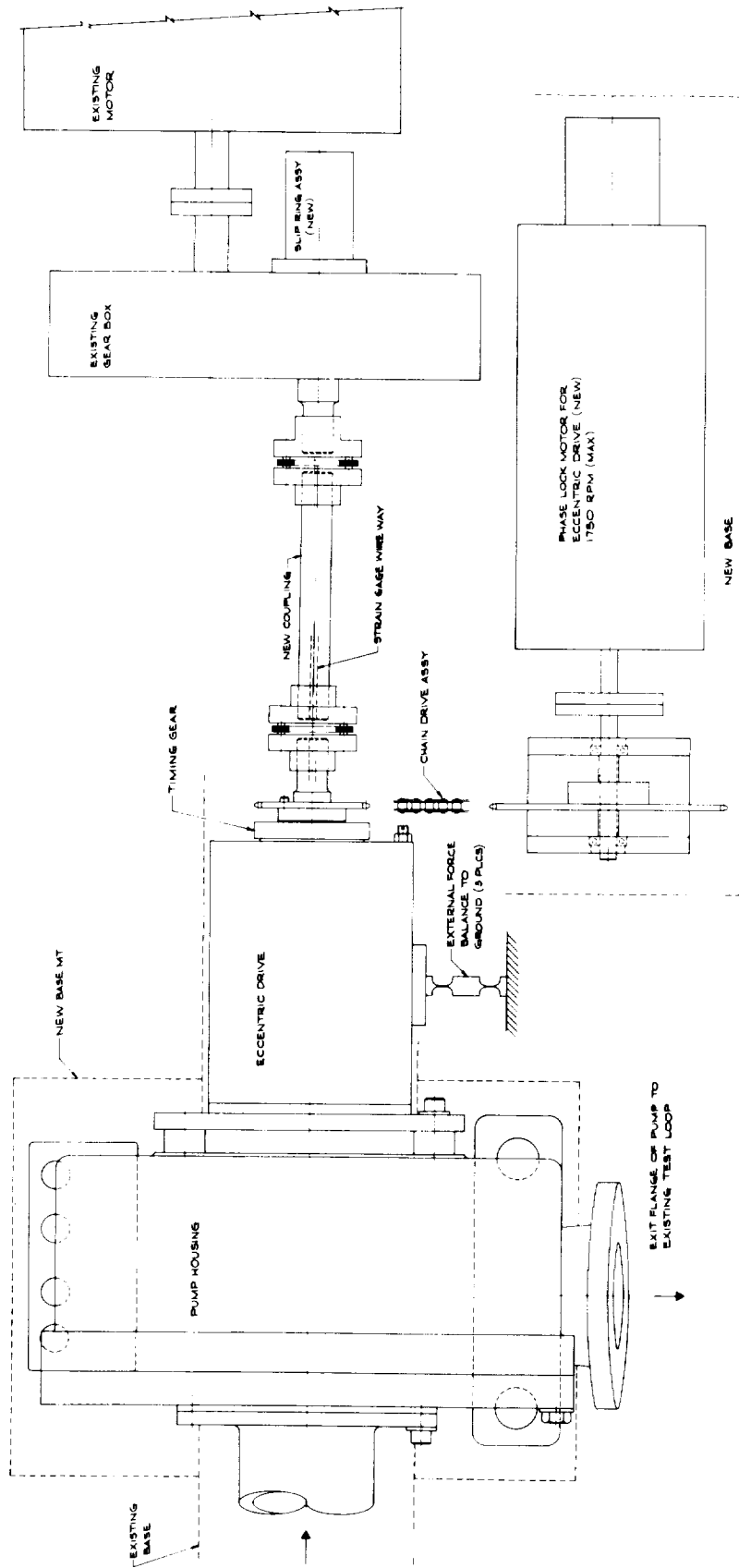
232

Figure 2. Schematic planview of the mechanical layout of the Rotor Force Test Facility.

EXISTING MOTOR

SLIP RING ASSY (NEW)

EXISTING GEAR BOX

PHASE LOCK MOTOR FOR ECCENTRIC DRIVE (NEW) 1750 RPM (MAX)

NEW BASE

NEW COUPLING

STRAIN GAGE WHEE WAY

TIMING GEAR

CHAIN DRIVE ASSY

NEW BASE MT

ECCENTRIC DRIVE

EXTERNAL FORCE BALANCE TO GROUND (3 PLCS)

PUMP HOUSING

EXIT FLANGE OF PUMP TO EXISTING TEST LOOP

EXISTING BASE

233

10,11). Specifically this involved finding the relations between the unsteady pressures and flow rates at inlet and at discharge as a function of the frequency of the unsteady components of the flow and of the mean flow conditions. A schematic of this system, known as the Dynamic Pump Test Facility (DPTF), is included as Fig. 3. The mechanical system of the Rotor Force Test Facility (RFTF) described above is being installed in the lower left-hand corner in

SIREN VALVE
PHASE-LOCK
DRIVE

SILENT THROTTLE
VALVE

DOWNSTREAM
SIREN VALVE

HYDRAULIC CONTROL

TURBINE METER

DOWNSTREAM
ELECTROMAGNETIC
FLOW METER

DOWNSTREAM LDV
MEASUREMENT SECTION

RESERVOIR-
HEAT EXCH
&
AIR REMOVAL

AIR BAG

DOWNSTREAM FLOW
SMOOTHING SECTION

3.5 MW LASER

15 6 KW
12000 RPM
DRIVE

VOLUTE

UPSTREAM SIREN
VALVE

TRANSPARENT HOUSING
& IMPELLER

WINDOW

UPSTREAM FLOW
SMOOTHING SECTION

PHOTO MULTIPLIER & UPSTREAM
LDV MEASURING SECTION

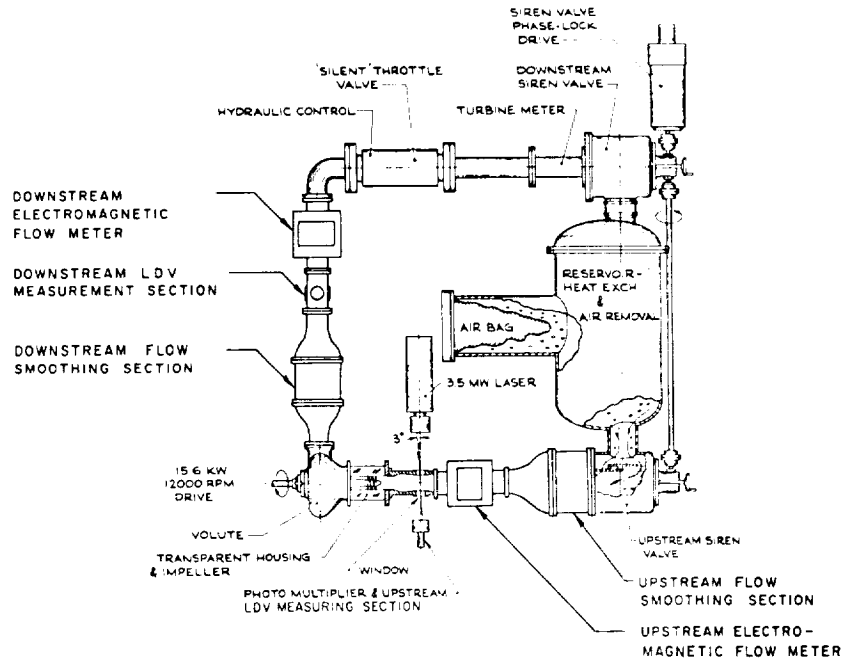UPSTREAM ELECTRO-
MAGNETIC FLOW METER

Figure 3. Schematic planview of the Dynamic Pump Test Facility

place of the impeller/volute system depicted in the Fig. 3. The DPTF included two flow fluctuators (siren valves) with phase-lock drive systems similar to that described above for the new eccentric drive system as well as instrumentation for measurement of the small oscillatory perturbations in pressure and flow rate. In the context of the present experiment these will again be utilized at a later stage to investigate whether flow fluctuations are associated with impeller whirl or whether they can induce impeller whirl. From a global dynamic point of view it is possible that the entire system of fluctuations (mechanical and hydraulic) may have to be represented by a global transfer function.

CONCLUDING REMARKS

Though bereft of results this paper is intended to highlight the lack of experimental evidence for whirl-exciting fluid forces arising from the flow through turbomachines. We hope that the experimental facility described above will be valuable in providing such evidence.

234

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